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X-RAYS

Past and Present

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PREFACE

A GLANCE at the chapter headings of this book may be somewhat alarming in view of the magnitude of the work that is suggested. To produce a scientific treatise of such a comprehensive nature in one small volume would be an impossible task, and we hasten to assure the reader that we have no such ambition.

We have set out to tell the story of X-rays for the benefit of the interested and enquiring layman because we believe that no general account of this fascinating branch of science is so far available for him. We have attempted to sketch a panoramic view of the subject, tracing its development in broad outline and indicating, with explanatory remarks, its bearing and the importance of its influence on modern scientific thought. We have also recorded all the important practical applications of X-rays, both scientific and industrial.

The full value of new discoveries in promoting our everyday comfort and well-being is not always immediately apparent. The general public are interested in the subject of X-rays, not only because of their value in medicine, surgery and industry, but also from a more fundamental point of view. As science is to a certain extent capable of accurate interpretation in non-technical language, we have endeavoured to explain our subject in a manner which imposes no necessity for a preliminary scientific training.

We hope that our book will help to satisfy and at the

same time stimulate that popular interest which is such a valuable factor in scientific progress.

Chapters 10, 16, 17 will be found to deal with practical uses of X-rays in industry and will, we hope, serve to direct the attention of engineers and others to the potential value of this new technique in activities where hitherto its use has not been fully realised.

We wish to express our gratitude to our colleague, Mr. A. G. Warren, for very kindly reading the proofs and for many valuable comments.

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CHAPTER I

THE BEGINNINGS OF RADIOLOGY

THE discovery of the phenomenon of X-rays, in common with all other scientific discoveries, was the outcome of systematic research. It was not a bolt from the blue!

Physical science is of course the observation and correlation of material phenomena. It has existed and progressed during the whole history of man. Maybe it pre-existed him. The early search for cause and effect, the essential concomitant of reason, was the beginning of scientific research. This search involved the exploration of many avenues and, moreover, many blind ones before the broad highway of progress was reached.

The history of philosophy shows that as one system of thought has succeeded another each step has, as it were, diverged, owing to the wider conceptions which manifested themselves as experience accumulated. This state of things led to specialization, which in turn has produced that accuracy of knowledge which characterises modern science.

It is very difficult to assign a beginning to radiological research. As far as any scientific discovery is accidental, the term may be applied to the discovery of X-rays. Prof. Rontgen, when he made his discovery, was investigating the phenomena accompanying the passage of an electric current through a vacuum tube, but this was simply an extension of the work that was begun very many years earlier.

Probably the first important work of this kind was done

by Mr. Hawksbee, F.R.S., in 1705, and was followed by the investigations of the Abbé Nollet, in Paris, in 1753. Mr. Hawksbee observed that when he agitated mercury in a vacuum bright flashes were produced. He describes the flashes of light as being of a pale colour, which we now know is characteristic of electric discharge through mercury vapour. Mr. Hawksbee did not in any way associate this light with any electrical phenomenon, but described the mercury globules as becoming phosphorescent. He went on to develop these experiments and constructed an apparatus having a rotating spindle arranged so that he could rub one substance against another in a bell-jar from which the air could be exhausted. He rubbed amber beads and wool together in a vacuum and obtained his characteristic light. On repeating the experiment in the open air " very little light did ensue in comparison to the appearance of it in vacuo." Hawksbee was inclined to attribute this effect to heat. He next tried rubbing flint against steel, and although he obtained sparks in the air, he was unable to see them after he had withdrawn the air from his bell-jar. For his next experiment he employed glass and wool. His apparatus consisted of a glass globe about four inches in diameter, which he rubbed against " woollen . . . . such as is now commonly sold for gartering." On withdrawing the air from his bell-jar he obtained a fine "purple light " when he rotated the spindle. " Upon letting in a little air both the light and the colour did diminish . . . . What is further observable in this experiment was that the purple light which appeared seemed to be about the breadth of half-an-inch and about one in height ; being visible nowhere but on each arm of the brass spring where the glass in motion rubbed on the woollen." These experiments of Hawksbee really mark the beginning of Radiological Research. They were the first observation of the remarkable phenomena accompanying an electric discharge through a vacuum.

The rubbing together of certain bodies is the oldest known method of generating electricity, and the purple light which Hawksbee describes is typical of an electric discharge through the particular degree of vacuum which he used. It may be seen to-day in an X-ray tube which has deteriorated and has an imperfect vacuum.

The next notable record of experimental work upon these lines is that appearing in the discourses of the Abbé Nollet, published in Paris in 1753. The Abbé Nollet made use of a vacuum pump and also an electric machine, both of which had been invented in 1650 by Otto von Guericke. Nollet constructed egg-shaped glass globes, which he exhausted and then arranged to pass electric discharges through them by means of a chain connected to the electrical machine.

The next experiments on this question are of great historical interest. They are the work of Mr. William Morgan, to whom must be given the credit of being probably the first experimenter to produce X-rays. His work was directed to " ascertain the non-conducting power of a perfect vacuum." He read a paper having this title to the Royal Society, in February, 1785. It would appear from Morgan's paper that at this time the phenomena accompanying an electric discharge through a vacuum were well known. His apparatus consisted of a tube inverted over mercury and coated at the sealed end for about five inches with tinfoil for the purpose of electrical connection. Morgan previously prepared his apparatus and mercury by very careful boiling. Having obtained a very excellent vacuum in this way, he found that he could obtain no evidence of the passage of an electric discharge through the tube when the tinfoil was connected to the electrical machine.

It is of interest to note that Morgan regarded his vacuum as perfect and that he also assumed that his experiment proved the perfect vacuum to be a non-conduc-

tor. The point of outstanding experimental interest is that he mentions the elaborate precautions which he adopted to free his apparatus and his mercury from gas by carefully boiling it.

His paper continues: " If the mercury in the gage (this is his exhausted tube) be imperfectly boiled the experiment will not succeed; but the colour of the electric light which, in an air rarefied by an exhauster, is always violet or purple, appears in this case of a beautiful green; and what is very curious, the degree of the air's rarefaction may be nearly determined by this means: for I have known instances during the course of these experiments where a small particle of air having found its way into the tube, the electric light became visible and as usual of a green colour; but the charge being often repeated the gage has at length cracked at its sealed end, and in consequence, the external air by being admitted into the inside has gradually produced a change in the electric light from green to blue, from blue to indigo and so on to violet and purple till the medium has at last become so dense as no longer to be a conductor of electricity."

There is no doubt that Morgan succeeded in producing what is now often spoken of as a Coolidge vacuum, which is, of course, practically a non-conductor. On allowing a little air to enter his tube he produced the ordinary phenomena of an X-ray tube. The gas became split up into ions—or, as it is called, ionised. Of the meaning of this term we shall have more to say in a moment. The ions bombarded the glass walls of the tube and so produced fluorescence in the glass and also feeble X-rays. Morgan's mention of the fact that he was able to judge his vacuum by the colour of the fluorescence is also interesting. It is the first mention of a rough and ready method which is now in general use.

The next experiments were those of Sir Humphrey Davy, in 1822, who continued the study of electric dis-

charges in vacuo. Faraday took up this investigation at a somewhat later date in the course of the development of his theory of dielectrics. His observations mark the beginning of a series of most important and beautiful researches. Faraday observed that when two electrodes were sealed into a bulb and the air withdrawn, and an electric current passed, the resulting glow between the electrodes became split, as it were, and a dark space divided the glow. This space was known as the Faraday dark space.

In 1869 Hittorf published a paper on the conduction of electricity through gases, which was a continuation of Faraday's work, but he used higher vacua in his discharge tubes. He noticed, as more air was removed from the tube, what he described as a " light " proceeding from the negative electrode or kathode. This " light " caused fluorescence of the glass walls of the tube and also cast sharp shadows of any object placed between the kathode and the glass, which fact showed that it travelled in straight lines from the kathode. This was the first intimation of that immediate forerunner of X-rays, known later as kathode rays, which were independently discovered by Sir William Crookes and investigated most fully by him during the next ten years.

The beautiful and changing phenomena that accompany the discharge of electricity through a gas at different pressures are best shown by means of a long cylindrical glass tube, an inch or so in diameter, having an electrode sealed into each end. If the electrodes are connected to some source of high voltage electricity and the air is gradually pumped out, we find that when the pressure has been reduced to a small fraction of an atmosphere (a pressure of only a few millimetres of mercury) a discharge starts to pass through the tube in the form of a luminous line proceeding straight from one electrode to the other. As the pressure falls still lower the line widens out until it

fills the whole tube with a luminous glow. With still more exhaustion the glow splits up into a number of detached portions and recedes towards the anode, leaving a dark space in front of the kathode, which is itself seen to be covered by a soft velvety glow. This is the dark space observed by Faraday and is known as the Faraday dark space.

If now the air pressure is reduced still more, as in the experiments of Hittorf and Crookes, the glow around the kathode is found to advance and, as it were, to push the Faraday dark space before it, leaving another dark space, known as the Crookes dark space, between itself and the kathode. At the same time the discharge which Hittorf first described as proceeding in straight lines from the kathode and which, from the time of Crookes, has been known as the kathode stream or as kathode rays, begins to make its appearance. Gradually, with still further reduction of the gas pressure, the Crookes space extends until it practically fills the whole tube. The kathode rays are now produced in great abundance and the appearance of the tube is most striking, for wherever the rays reach the glass they cause it to fluoresce, the colour of the fluorescence depending upon the chemical composition of the glass. Although, as we shall see, it was many years before the fact was discovered, we now know that the bombardment of the glass by the kathode rays has another and much more important result—the production of X-rays.

The process by which a gas is rendered capable of conducting electricity is known as ionisation. A gas is made up of constituent particles, called molecules, which in turn are combinations of other units called atoms. It is now known that they are made up of a number of independent electric charges, some positive, some negative, but normally so balanced that the whole is electrically neutral—the total positive charge equals the total negative charge.

If something causes an electric charge to be detached from a molecule, thereby destroying its neutrality, ionisation is said to have been effected, and a gas particle in such a state is called an ion (or traveller). Various agencies, of which X-rays are one, are effective in producing ionisation of gases. Whenever X-rays pass through a gas, at either atmospheric or reduced pressure, a few of the gas molecules are ionised. How the effect is produced, or why only a certain number of molecules are acted upon by the rays, we do not know, although, as we shall see later, this has been for some years one of the most important questions in the whole science of physics.

In the case of gas contained in a tube having two electrodes sealed into it, such as we have described, the gas forms the completion of the electric circuit, and so long as no ions are present no current can pass between the electrodes. So soon as any ions are produced in the gas they are attracted—the positive ions to the negative electrode and the negative ions to the positive electrode, or anode, as Faraday called it. Arrived there, they tend to neutralise the charge on the electrodes, and so reduce their electric potential, with the result that a quantity of electricity flows from the battery (or whatever source of electricity is being employed to maintain it). A constant supply of ions in the gas thus means a steady flow of current in the electrical circuit of which the gas forms part—the gas has become conducting.

The remarkable phenomena we have described as attending the discharge of electricity through a partially evacuated tube must, then, depend on this process of ionisation. So long as the gas in the tube is at atmospheric pressure no appreciable current passes at all under the circumstances we have described, because the gas is almost entirely a non-conductor. Even if we had produced some ions, say, by letting X-rays fall on the tube, the current would have been extremely minute. It is when most of

the air has been pumped out of the tube that it begins to conduct readily. It seems that at these low pressures there are always a few free ions present, but these by themselves could not account for the magnitude of the current that passes—they can only start the process. Once ionisation is started, more ions are produced in great quantities by a process known as ionisation by collision.

Although partially evacuated, the tube still contains a very large number of gas molecules, so that some of the ions on their journey to their appropriate electrodes will collide with some of the gas molecules. Under certain favourable circumstances, if they possess sufficient energy, they may knock off unit charges from the molecules with which they collide, so producing more free ions. If the pressure of the gas is high, its molecules are closely packed together and the collisions will be frequent, so that the ion will not have had time to get up much speed before meeting with a molecule. It will probably, therefore, not have acquired sufficient energy to knock off a charge. It is when the gas pressure is reduced, so that the average distance an ion travels before suffering a collision (this distance is known as its " mean free path ") is comparatively large, that ionisation by collision becomes appreciable.

It will now be realised that the passage of a discharge must depend upon a number of factors. In the first place, there must be some free ions in the tube to start with, and secondly, the electric force between the two electrodes must be sufficient to impart to them the requisite speed. A third factor is that the pressure of the gas must be so reduced that they may have a free path of sufficient length. (The mean free path varies inversely as the gas pressure.) When all these conditions are properly filled a discharge passes through the tube. The various glows that have been described are found to indicate the places where ionisation by collision is occuring, and the two dark spaces may be

regarded as indicating the path of the ion which is free from collisions with gas molecules.

In a gas at atmospheric pressure ions frequently consist of groups of molecules, but at the low pressures which exist in discharge tubes the negative ions exist independently as free negative unit charges ; in other words, as free electrons, as will be seen in a later chapter. The positive ions are gas molecules which have lost a negative charge and are therefore of much greater mass and less mobile than the negative ions.

In a well exhausted Crookes tube the Crookes dark space reaches from the kathode to the walls of the tube, and throughout that space streams of positive ions are being attracted towards the kathode. In its neighbourhood they will have their greatest activity and will have acquired a big velocity when they reach it. They will therefore be able to ionise any gas molecules in the immediate neighbourhood of the kathode, even possibly to knock ions out of the negative electrode itself. The free negative ions then produced will be repelled from the vicinity of the negatively charged kathode with great force and it is these negative ions (really free electrons) which constitute the kathode rays, investigated so carefully by Crookes and first demonstrated by him at the British Association meeting of 1879.

Crookes formed very accurate ideas of what was happening inside his tubes, although he regarded the kathode rays as a stream of negatively charged moving particles of molecular dimensions rather than as the infinitely smaller particles which we now know them to be. His observations led him to conclude that in these vacuum tubes we had to deal with what he called " radiant matter," a conception which had already been put forward by Faraday. It is interesting to quote from Crookes' original paper to the British Association : "In these highly exhausted vessels the molecules of the gaseous residue are able to dart across the

tube with comparatively few collisions, and radiating from the pole with enormous velocity, they assume properties so novel and characteristic as to . . . . justify the application of the term borrowed from Faraday, that of Radiant Matter." Crookes states that the pressure in his tubes was about one millionth of an atmosphere, or about .00076mm. of mercury.

The study of the discharge of electricity through a vacuum tube has always been an interesting and fascinating one. The discovery of kathode rays and the beautiful experiments shown by Crookes stimulated a new interest in the subject, which led ultimately to the discovery of Rontgen's X-rays, of which kathode rays were the immediate precursors.

CHAPTER II

RONTGEN'S DISCOVERY

ALTHOUGH, as we have seen, the existence of a light or radiation proceeding from the negative electrode of a highly exhausted vacuum tube was first described by Hittorf in 1869, it was not until Sir William Crookes published the results of his independent work to the British Association, ten years later, that the full significance and importance of the subject was realised. Crookes examined and studied these kathodal radiations with a true scientific thoroughness which must remain a model for scientific investigators for all time. He showed that the kathode rays caused brilliant fluorescence of the glass walls of the vacuum tube and that many natural earths and other substances placed in the tube would fluoresce with vivid colours under their influence. If a solid object, such as a mica screen, were introduced between the kathode and the glass wall, a sharp shadow of the screen appeared, showing that the rays travelled in straight lines. To show that they possessed energy he constructed a tube in which the rays impinged on a light windmill, which was thus caused to rotate; but it must be admitted that the conclusions drawn from this experiment were hardly justified. Crookes proved also that these rays issued normally from the surface of the kathode, so that by using a kathode with a concave surface they could be made to converge towards a point. If the rays were thus focussed on to a piece of glass it was readily melted by the heat produced. Even plati-

num foil was rapidly raised to incandescence in this way and eventually melted.

Perhaps the most important of all Crookes' observations on these kathodal radiations was the fact that they could be deflected by a magnet, for it led him at once to what we now know to be the true conclusion as to their nature: that they consisted of streams of material particles, moving at a very great speed and each one carrying a charge of negative electricity.

Let us consider for a moment how this conclusion was arrived at. One of the fundamentals of Clerk Maxwell's electromagnetic theory is that a movement of lines of electric force, such as Faraday had pictured as radiating from a charged body, is always accompanied by a field of magnetic force. On this theory, then, a moving electrified particle, or a succession of such particles, would be equivalent, in the magnetic sense, at any rate, to an electric current. This was not only theory, for Rowland had produced experimental evidence of the deflection of a compass needle by the movement of an electric charge. Crookes decided that his experiments showed the reverse case, the deflection of a succession of charged particles by a magnet, and from the direction of the deflection he concluded that the charge they carried was a negative one.

Crookes' demonstration of the properties of the kathode rays, or the kathode stream, as it was afterwards called, deservedly created world-wide interest, for it may be said to form a landmark in scientific progress. The remarkable phenomena which he had investigated in so able a fashion opened up a whole new vista of scientific thought, but in spite of the work of many experimenters and the production of the new Crookes tubes all over the world, so complete had been Crookes' observations that little more was added to the knowledge of the subject for many years.

It must not be supposed, however, that his conclusions were accepted without question. With his experimental

observations none could quarrel, for they were repeated in every scientific centre, but his deductions and his explanation of the phenomena gave rise to a storm of controversy. His material particle explanation was generally accepted in this country, but the conception of " matter in a fourth state "—of flying molecules—was perhaps too revolutionary for general acceptance.

Hittorf at once challenged Crookes' conclusions and denied the possibility of any propagation of particles of matter. He was followed by the bulk of the German physicists, who preferred to regard the kathode radiation as another manifestation of wave motion in the æther, that is to say, as another form of ordinary light. Wiedemann in particular published a paper advancing this view in 1883.

The year 1883 also produced what was perhaps the first result of the impetus given to scientific thought by Crookes work, for it was in this year that J. J. Thomson first put forward a theory of electric discharge through gases based on the principles of electrolysis—conduction by ionisation. For many years the process of electrolysis of a liquid had been regarded as the splitting up of the molecules into two parts, a positive ion and a negative ion. Thomson pictured a similar process going on in the rarefied gas of a discharge tube, the gas molecules absorbing energy from the electric field to which they were subjected and so becoming decomposed, as it were, into free atoms, a theory which formed a very useful starting point for the study of the complicated phenomena attending the discharge of electricity through gases.

Crookes, in the meanwhile, in common with many other workers, was attempting to obtain direct experimental proof of the existence of the negative charge associated with the kathode stream. These efforts were unsuccessful because, as we know, the experiments were complicated and the results masked by the ionisation of the residual gas in the discharge tube. The nature of the kathode dis-

charge still remained a matter of controversy, and the question of " radiant matter " or " æther waves " was still undecided.

Matters remained much in the same state for the next ten years or so. At that time Hertz, who was working at Bonn on the experimental proof of Maxwell's theories, took up the study of discharge in vacua. He found that the kathode stream would pass right through a very thin film of gold or aluminium placed in its path. On his death, in 1894, his work was continued by his pupil, Lenard, who, by sealing a very thin aluminium window into the wall of a discharge tube and directing the kathode radiation on to it, succeeded in bringing the kathode rays out of the tube into the outside air. He found that they still retained their property of producing fluorescence and that they were very quickly diffused in air at ordinary pressures, but that they would travel very great distances in a rarefied atmosphere. A part of these rays could be deflected by a magnet, and, in addition to being able to pass through thin films of solid substances, Lenard incidentally remarks that they can pass through the hand. We know now, of course, that part of Lenard's results were due to the still undiscovered X-rays.

The immediate result of all this was to lend strong support to the æther wave theory of the kathode stream. Whilst it was possible to imagine a form of light which would pass through objects opaque to ordinary light, the difficulty of picturing the passage of molecules of matter through solid obstacles seemed to offer an insuperable objection to Crookes' theory.

The supporters of what we may call the materialistic theory, however, did not have long to wait for further encouragement for their side of the case, for in 1895 Perrin succeeded in producing experimental proof of the negative charge associated with the kathode stream. He constructed a vacuum tube containing what is known as a

Faraday cylinder—that is to say, a small metal cylinder with an opening at one end and surrounded by an outer metal guard cylinder, also with an aperture at the end. The outer cylinder was connected to earth and the inner to an electroscope. The vacuum tube was so arranged that the kathode stream could be deflected by a magnet and made to enter the metal cylinders. When it did so the electroscope at once showed that the inner cylinder acquired a negative charge. Now, the presence of the earthed shield ensured that it could not be affected in any way by any external electric charges, and the negative charge it acquired must therefore have been carried into it, through the hole, by the kathode stream.

But Perrin did more than this. If the kathode stream consisted of electrified particles it should be possible to deflect the particles by means of an electrostatic field; that is to say, to attract or repel them by bringing an electric charge near them, just as an electrified pith ball is attracted or repelled by bringing a charged body near it. A slight indication of such an effect had been recorded by Goldstein as far back as 1876, when experimenting with Hittorf's "negative glow light," and Perrin now succeeded in obtaining a slight but definite deflection of the kathode stream by electrostatic means. He had to employ very high electric potentials to obtain an appreciable effect. Thomson, some time later, constructed a discharge tube with two parallel metal plates inside it, between which the kathode stream passed. The plates were connected to some source of electric potential—an electric machine or a battery—and being very close together an intense electric force was set up between them. In this way he was able to obtain a deflection of the kathode stream with as little as two volts difference of potential between the plates. We shall hear more of this experiment in a later chapter, for it led to that brilliant investigation by which Thomson finally settled all doubt as to the nature of the kathode

stream, and opened up a new era of scientific progress, of which we are only now reaping the practical benefits.

Let us return, however, to the year 1895. In spite of Perrin's experiments the controversy continued unabated. The passage of the kathode stream through solid obstacles was the main support of the " wave " theorists, who objected—quite reasonably—that it was impossible for molecules of matter to pass through solid substances in this fashion. On the other hand, the " material " or " corpuscular " school relied on the magnetic deflection of the kathodal discharge and replied that it was not necessary to suppose that the molecules actually passed *through* a metal plate. It was suggested that when the charged molecule hit one side of the plate it set up an electrical action which was passed on from molecule to molecule through the plate to the other surface, and finally sent off a fresh molecule from the other side of the plate.

A very excellent summary of the position at this period was given in a lecture by Sir George Stokes some time later. Showing a Crookes tube containing a mica screen with a small hole in it placed in front of the kathode, he said, " Nobody, I suppose, denies that there is matter propelled, but there has been considerable difference of opinion as to whether the matter propelled is of the essence of the phenomenon or whether it was something merely accidental. Mr. Crookes held that it was of the essence of the phenomenon and that we had here really a stream of molecules, and I must say, for my own part, I believe he was right. But some foreign men of science held that the projection of matter is altogether a secondary phenomenon and that what comes through this small hole is really only a process which goes on in the ether—something so far in the nature of light, but yet differing from ordinary light most markedly in the property of being deflected by a magnet. To illustrate what I mean by saying something secondary, Professor Wiedemann, who

holds the opinion that it is of the nature of light or a process going on in the æther, imagines that the projec- of matter has no more to do with the phenomenon than the path of a cannon ball has to do with your hearing the sound of the cannon."

Such, then, briefly was the extent of the knowledge of the phenomena attending the discharge of electricity through a well exhausted vacuum tube in the autumn of 1895, when Professor Wilhelm Konrad Rontgen, professor of physics in the University of Wurzburg, Bavaria, made

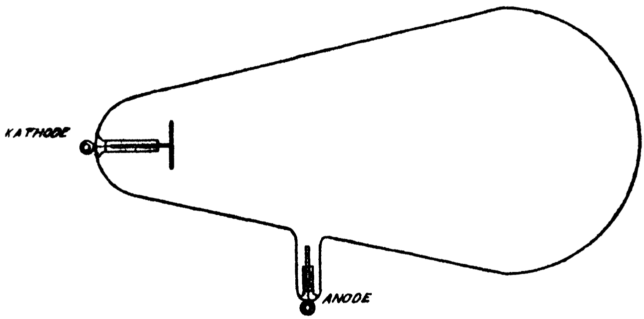


FIG. 5. TYPE OF VACUUM TUBE WITH WHICH RONTGEN DISCOVERED X-RAYS.

his famous discovery. Rontgen was one of the many scientific workers who, in all parts of the world, had been puzzling over this problem of the vacuum tube. Working one day in his laboratory with a Crookes tube (or Hittorf tube, as it was called in Germany), he noticed that when the discharge was passed through the tube some crystals of barium platinocyanide spread on a piece of card some yards from the tube became brilliantly illuminated, although the visible light from the tube was screened off by black paper. He found that various substances placed between the tube and the card cast a shadow on the crystals, and in this way he traced the origin of the light back to the tube. In this simple fashion was so great a discovery achieved.

Rontgen's discovery of the new radiation has often been described as accidental, but in reality the only accidental circumstance connected with the matter was the fact that their detection had been missed for so many years, for X-rays had been produced in considerable quantities by Hittorf and Crookes and the host of physicists who followed in their footsteps. Sir William Crookes has in fact told of his annoyance on one occasion at finding that a batch of photographic plates which he was using in his laboratory were found to be fogged and how he returned them to the makers who were at a loss to account for the defect. It was only when he heard of Rontgen's discovery many years later that he understood that his plates had been fogged by the X-rays produced from his own vacuum tubes. One form of his tube, that in which he showed the focussing of the kathode stream on to a piece of platinum, was, as we shall see later, almost exactly the same as the focus type of X-ray tube which soon became the standard tube for all X-ray work.

Sir Herbert Jackson was another investigator who narrowly missed the great discovery. He was one of the many experimenters who were studying the phosphorescence of various substances when bombarded by kathode rays. He was seeking a substance which would produce only ultra violet light—that light of wave length just a little shorter than that of violet light which is invisible to the human eye, but which has such powerful chemical and other effects. In the course of his experiments he noticed that certain substances outside his vacuum tubes were fluorescing. He attributed this to the ultra violet radiations. Next he made a tube like Lenard's with an aluminium window and obtained an even more marked effect. Then, as he himself has said, " Just as I was puzzling over this, Rontgen's discovery was published, and I saw the explanation of my own results."

Rontgen, it is interesting to notice, discovered his

rays—the X-rays as he called them " for the sake of brevity "—by the fluorescence of barium platinocyanide, the substance which is still the most greatly used for rendering the rays visible. It was no mere accident that a card coated with so uncommon a compound (a fluorescent screen as it is called) should be lying about in his laboratory. Barium platinocyanide had been found to be one of the most brilliantly fluorescing materials under the action of the invisible ultra violet light, and Rontgen has said that he was looking for invisible rays that might be given off by his vacuum tube. Manifestly, to regard the striking success of his search as accidental would be wrong. Rather must we regard it as the culminating triumph of more than two centuries of patient scientific research, which started with the invention of the air pump by Von Guericke, in 1650, and was developed by Hawskbee, Faraday, Hittorf, Crookes and many other important but lesser known workers.

CHAPTER III

THE NATURE OF VISIBLE LIGHT

ALTHOUGH a period of some sixteen years had elapsed between the publication of Crookes' work and Rontgen's discovery of the new rays, the actual nature of the kathode stream was still just as much in doubt as ever, and the question was now complicated by the problem of the new rays. These we now know are similar to ordinary light, but it was a long time before this fact was definitely proved.

Before we can appreciate or understand the discussion that ensued on these points, or the vast amount of speculation and controversy which occurred before the position was finally cleared up, we must pause to consider some of the properties of ordinary visible light and the facts that were known at that time as to its nature, and how those facts had been arrived at.

Speculation as to the nature of light has probably existed so long as man has possessed the power to reason, and certain elementary optical facts have been known from the earliest times. Mirrors and burning glasses were well known to the ancients. They taught that light travels in straight lines and also understood the law of reflection. As to the actual nature of light, we find Pythagoras, more than five hundred years B.C., teaching that vision was caused by particles projected from the surface of objects into the pupil of the eye, whilst a century or so later, in 350 B.C., Aristotle combated this emission theory and

maintained that light was a mere quality or action of a medium which he named the pellucid—a happy, though perhaps a chance, anticipation of the theories of two thousand years later ! The ancient philosophers knew, too, that a ray of light is refracted, or bent, when it passes from one medium to another of different density as from air to water, or glass to air, but the law of refraction was not discovered until it was arrived at by Snell, about 1621.

This period—the seventeenth century—may be said to mark the beginning of the real science of optics. In 1666 Newton made the important discovery that white light consists of a mixture of lights of different colours which can be separated out by refraction just as happens in the formation of a rainbow. Grimaldi, a year before, had published an account of his experiments on the spreading out of light in all directions after passing through an aperture, an effect which he named " diffraction," and Romer, in 1676, by means of observations on Jupiter's satellites, made the great discovery that the propagation of light takes a definite time and even calculated its velocity with very fair accuracy. Up to that time it had been generally supposed that the transmission of light was instantaneous. Descartes, for example, who published his " Dioptrics " in 1638, imagined light to be due to a pressure transmitted instantaneously through a perfectly elastic medium filling all space—a view very similar to that of Aristotle. This idea of a special light transmitting medium had prevailed from the earliest times and we find suggestions of it in the writings of many of the early philosophers.

It was in 1678 that the science of optics took on its modern form, for in that year Huygens definitely formulated the undulatory theory of light. Light was regarded as due to undulations or wave motion in an elastic all-pervading medium, which now became known as the æther. Although Huygens was able successfully to

explain many of the known facts, such as reflection and refraction, by means of the wave theory, he could not account for the rectilinear propagation of light and the formation of shadows, a fact which soon brought discredit to the whole theory. If light consisted of waves it should spread round corners, it was argued, just as sound does. The truth is that light *does* bend round corners, but only to a minute extent, on account of its very small wave length. Grimaldi had already shown this by his diffraction experiments, although the significance of his work had not been realised at the time.

It was largely due to these difficulties that Newton was led to discard the new wave theory and to formulate an emission theory which, like that of Pythagorus, assumed that a luminous body continually emitted a stream of very minute light particles or corpuscles, which, striking the retina, caused the effect of vision. The theory was able to explain reflection and refraction and accounted well for the rectilinear propagation and the formation of shadows. There were, however, many difficulties into which we need not enter. We will refer only to one. It was necessary to explain how a stream of light corpuscles, striking the surface of a transparent medium, such as a piece of glass, might be both reflected and refracted. Here Newton was forced to assume the existence of an æther in which his particles travelled and which was set in vibration when the particles struck the surface. These vibrations he assumed periodically to assist and retard the progress of the corpuscles, endowing them with what he called "fits of easy transmission or reflection." We mention this ingenious theory here, not only because, backed by the weight of Newton's authority, it held almost undisputed sway for nearly a century and is therefore of great historic interest, but also because it has in some respects striking points of similarity to the views which the work of recent years is now forcing upon us. Preston, in his

Theory of Light (1890), remarks that it would be quite possible to frame a satisfactory emission theory of light, but that we should find in doing so we had to " endow the corpuscles with the periodic characteristics of a wave motion, and when this is introduced the corpuscles themselves may be eliminated, for the wave motion alone sufficiently explains the phenomena." As will be seen in the sequel, it is by no means so certain now that wave motion alone *is* capable of accounting for all the known facts, and one of the greatest problems of modern physics is to reconcile the wave theory, which seems indispensable, with those modern counterparts of Newton's corpuscles, the energy quanta, the existence of which now appears inevitable, and of which we shall have more to say in a later chapter.

Throughout the eighteenth century Huygens' undulatory theory was completely eclipsed by the corpuscular theory, but it was brought back into prominence after the discovery by Dr. Young, in 1802, of the phenomenon of interference. Young allowed the light coming through a narrow slit in a shutter to fall on a screen perforated by two pinholes very close together. The light which passed through the pinholes fell on another screen and where the two patches of light overlapped he obtained, instead of uniform illumination, a series of brightly coloured bands. If one of the holes was covered the bands disappeared. Young explained these effects in terms of a wave theory, but it was not until some twenty years later, when that great French scientist, Fresnel, produced interference by other methods, that his work was generally accepted.

The subject of interference is of such extreme importance in the theory of both visible light and X-rays that we must now consider what it is and how it is produced, and first we must try to fix our ideas as to the transfer of energy by means of waves.

We know that light is a manifestation of energy, if only

because it will heat an object on which it falls. It has been proved that it takes a definite time to travel from place to place. The Newtonian corpuscular theory imagined this transfer of energy to be carried out by minute particles shooting across space like bullets from a gun. The undulatory theory considered that the energy travelled through a hypothetical non-material substance known as the æther in continuously spreading waves, analogous to the manner in which we know sound is carried through the air or the way in which disturbances may spread over the surface of water in the form of waves.

Suppose we drop a pebble into a still pond. A circle of ripples will spread out from the spot where the pebble hit the water as the disturbance caused by the pebble travels outwards. A wave of energy derived from the falling pebble is spreading over the surface. We cannot see the energy, but we see its effect—the ripples which result from it. At any particular spot on the surface the water will be alternately piled up to form the crest of a ripple or depressed into a trough, and this will happen at regularly recurring or periodic intervals of time. Such a series of waves following one another is called a " wave train," or " train of waves," and the distance from one crest to the next or from one trough to the next will be found to be the same for all the waves of the train, and is called the wave length. The waves follow each other at regular intervals of time, known as the periodic time, and the number that pass any one spot in a second is called the frequency or periodicity. It is easy to see that for any particular system of waves the velocity of propagation of the disturbance—that is, the distance it travels in one second—is equal to the wave length multiplied by the frequency. Writing this in algebraic form and using the symbols usual employed, V for the velocity, λ for the wave length, and ν for the frequency, we have the simple relationship

$$V=\lambda\nu$$

and we see that, for a particular velocity, the shorter the wave length, the greater must be the frequency, since the product of the two must remain constant.

We must keep it clear in our minds that it is only the energy that is travelling outwards in the wave—there is no flow of water. The water, as will be shown by a piece of cork floating on the surface, will be lifted up and down at regular intervals as the waves pass, but not moved bodily forward. Each particle of water will merely oscillate or execute what is called a periodic motion.

Now, Young obtained his coloured bands by allowing two beams of light to overlap. What, then, will be the effect on the surface of our pond if we have two systems of similar waves travelling across it and meeting each other, as might happen if we had dropped in two exactly similar pebbles in precisely the same manner. Obviously the result must be different at different spots, because in some places it must happen that both the waves are doing exactly the same thing to the water surface—both are lifting it into a crest or both are depressing it into a trough—both are displacing it in the same direction. Here the disturbance of the surface will be increased by the joint action of the two waves, but there will be other places where both the waves are trying to displace the surface in opposite directions, and at these spots the result must be a lessening of the disturbance. If, as we have supposed, the two waves are exactly similar, there must be some places where they are exactly opposing each other—places where one wave left to itself would be producing a crest or the other a trough—and the result of the two acting together is that nothing happens at all—the surface is undisturbed.

This effect is what is meant by the interference of two waves. Actually what has happened is that the energy that was travelling out in each of the waves has been redistributed—it has been removed altogether from some

places and piled up in others. The places where the result is a maximum are the places where the two waves are acting exactly in the same way. Since the fundamental characteristic of wave motion is that every part of the wave is continually repeating itself at intervals of a wave length, it follows that we can find out what the two waves are doing when they meet at any particular spot by measuring out to scale the number of wave lengths along the paths of the two waves—a simple question of geometry. Worked out in this way, it can be shown that the effect of the two similar waves travelling over the surface of a pond or of the two light rays in Young's experiment is to produce alternate areas of reinforcement and interference. With short waves these areas are found to be close together; with long waves they are more widely separated. They indicate alternate regions of disturbed and still water, or, in the case of light waves, alternate areas of light and darkness.

Young, in his original experiment, obtained not light and dark bands, but bands of brilliant colours. This was because he used white light, which Newton's spectrum had shown to consist of a mixture of all the colours. If the experiment is carried out with light of a single colour—monochromatic light, as it is called—alternate light and dark bands are produced just as the theory predicts. If red light is used, the bands are found to be wider and more spaced out than with blue light. We have seen that the wider spacing is associated with longer wave length, so that the wave length of red light must be greater than that of blue and its frequency less. Similarly, it is found that the wave length steadily decreases as we pass through the spectral colours from red to blue. An interference experiment carried out with white light produces a series of bands of different widths superimposed on and overlapping one another and representing all the component colours of the original light. The light band of one colour will

overlap into the dark band of another, and so, instead of alternate light and darkness, a brilliantly coloured pattern results.

Interference may be produced under the right conditions with wave motion of any type—whether it be waves on the surface of water, sound waves, which we know are waves travelling to our ears through the air or through some material substance—or whether it be waves such as light, heat or electric waves in some medium which at present is beyond our comprehension. Whatever the form in which the energy of the wave manifests itself to our senses, we shall find a redistribution of that energy. There will be an intensified sound at one place and a diminished sound at another, or an increase of illumination at one spot and a reduction of illumination or darkness at another whenever the two trains of waves arrive together. If either of them is prevented from arriving uniform sound or uniform illumination results.

Although Dr. Young, quite correctly, explained his remarkable and beautiful results by reintroducing Huygens' discredited wave theory of light, it was, as has been said, many years before his explanation was accepted. The physicists of his day were as sceptical as their successors of a century later, when the nature of the kathode stream and Rontgen's X-rays was under discussion. They had seen something very like his coloured bands before in Grimaldi and Newton's diffraction experiments. In these light had been passed through apertures in darkened rooms much as in Young's experiment, and it had been observed that the edges of shadows cast by the light were surrounded by brightly coloured fringes. It was thought, therefore, that Young's result might be only another example of diffraction. Only when Fresnel, with great ingenuity, showed how to produce interference by *reflecting* two beams of light along paths of different lengths, thus avoiding the doubtful effects of apertures, was the

wave theory generally accepted, for it was extremely difficult to account for the results on any other theory.

Fresnel proceeded from one success to another, for he was now able to unravel the mystery of diffraction which had hitherto remained unexplained. He recognised that light does bend round the corners into the shadow of an obstacle to a minute extent, as a wave theory expects it to do, and he showed that the coloured fringes are caused by interference between the disturbances spreading around the obstacle from different parts of the original light wave. The successful explanation of diffraction was a new triumph for the wave theory, and, apart from that, was of the utmost importance, since it led at a later date to the production of one of the most valuable scientific tools that have ever been devised—the diffraction grating—and this again led many years later, as we shall see, to that brilliant inspiration of the physical mathematician von Laue which solved once for all the vexed question of the nature of X-rays and laid the foundation of the wonderful new science of X-ray spectroscopy.

The construction of a diffraction grating is a triumph of instrument making. Picture the difficulties involved in ruling a piece of glass with a vast number of parallel lines spaced out accurately at the same distance apart, 20,000 or more—even as many as 40,000 to the inch—for this is how a diffraction grating is made. The spaces between the lines form very narrow apertures through which light can pass, and the spreading waves from each of these tiny windows interfere so that their energy is concentrated along certain directions where they reinforce one another. It can be shown that these paths of reinforcement are spaced out regularly in accordance with the wave length of the light, and so the different colours are spread out in the form of a spectrum similar to that produced by a prism. Reflection gratings are also made in which the lines are ruled on a metallic reflector. Light is reflected from the

spaces between the lines with results similar to those of the transmission grating. Crude diffraction spectra may be observed in the simplest possible fashion by viewing a distant light through a piece of regularly woven material, such as a fine handkerchief or, better still, a silk umbrella.

The diffraction grating has been described above as among the most valuable of scientific tools. Measurements of an accuracy and smallness hitherto undreamed of were made by its aid, and it has been the means of determining with wonderful accuracy the actual length of the waves of visible light. Light from the middle of the spectrum is found to have a wave length of the order of $\frac{1}{50,000}$th of an inch. Since light has been found to travel at the enormous speed of 186,000 miles per second, it follows, from the relation that has been given on page 38, that the frequency must reach the gigantic figure of nearly 6×10^{14} or 600 million millions per second ! Of the shortest waves that are visible—those that appear violet in colour—a train of no less that 72,000 could be required to spread over an inch—whilst at the other end of the spectrum 33,000 of the longest visible red waves would occupy the same space. It has also been found that the spectrum does not end with what the eye can see, but that at either end there are waves of still shorter or longer wave length to which the human eye is blind. At the short wave end these ultra-violet rays, as they are called, are notable for their chemical and photographic effect, whilst the invisible rays of long wave length—the infra-red—manifest themselves chiefly in the form of radiant heat.

The discovery of interference and the explanation of diffraction resulted, as has been said, in the resuscitation of Huygens' wave theory and made it reasonably certain that light must consist of vibrations or periodic changes of some sort, but it gave no indication of the actual nature of those changes. Science had made great strides in those early years of the nineteenth century, but there was still

much to learn and much to be explained. There was, for instance, the peculiar phenomenon of polarisation, which could not even now be accounted for.

As far back as the year 1669, one Erasmus Bartholinus, a Danish philosopher, had noticed that when a beam of light passed through certain crystals part of it was refracted in an unusual manner. Huygens followed up his observations and found that when this irregularly refracted light emerged from the crystal it exhibited certain peculiarities, in which it differed from ordinary light. The effect may be most easily observed with two pieces of tourmaline crystal. If the light which has passed through one tourmaline crystal is made to fall on a second tourmaline, it will only pass through when the axes of the two crystals are parallel. As one is turned round the light passing through the second crystal diminishes until, when they are at right angles—" crossed " as it is termed—none gets through at all.

Light in this peculiar state is said to be polarised. Huygens was unable to explain polarisation and Newton had regarded it as a strong argument against the wave theory. It was left to Fresnel to clear up the mystery. The reason that so many great philosophers had failed to discover the solution was that they had all thought of waves of light as longitudinal vibrations, that is to say, vibrations parallel to the direction in which the light is travelling, whereas the vibrations are really at right angles or transverse to the direction of travel. Sound waves were known to consist of longitudinal vibrations in the atmosphere—a series of rhythmical compressions and rarefactions which cause the air particles to vibrate backwards and forwards along the line of travel of the wave—and it was perhaps only natural that the undulations of light should be thought of as similar, rather than as the little known transverse vibrations.

Once the idea of transverse waves had been arrived at,

the explanation of polarisation presented little difficulty. We know that a stretched string may be made to vibrate either along its length—the unpleasant noise produced by scraping lengthwise along a violin string is evidence of this—or transversely from side to side, as we see very plainly if we jerk one end of a stretched rope rhythmically up and down. If now the rope passes through a narrow slot, longitudinal vibrations can be in no wise affected, but transverse vibrations will only be able to pass through the slot if they are parallel to the length of the slot. If there were a second slot they would only be able to pass through it if it were parallel to the first. Turned at right angles to the first, it would effectually stop the transverse vibrations that reached it.

The explanation of polarisation must be, then, that light vibrations are transverse, and the crystals act as slots which only allow vibrations in a particular plane to pass through them. The first crystal, referred to as the polariser, sorts out, as it were, the light waves that fall on it and only allows vibrations that occur in one particular plane to pass through, and this light is said to be polarised. The light energy is concentrated in one plane, and at right angles to that plane there is none. The second crystal, called the analyser, corresponds to the second slot and acts as a detector of polarisation. There is another method of polarisation, discovered by Malus, in 1808, which will be of special interest when we come to consider the polarisation of X-rays. He found that light is polarised when it is reflected from a mirror at a particular angle. The actual value of the polarising angle depends upon the reflecting surface.

The possibility of transverse vibrations had been guessed at by Hooke as far back as the year 1672, but the suggestion had been lost sight of. Fresnel appears to have been the first to think of this type of wave as the explanation of polarisation. In 1846, working with Arago, he

linked up these new ideas by showing that two beams of polarised light could produce interference if the two polarisers were parallel, but not if they were at right angles. Henceforth light was recognised as a manifestation of some form of transverse wave motion, and the Newtonian corpuscular theory was dead. Fresnel's work had dealt the final blow to a theory which had reigned supreme for more than a century.

It is characteristic of scientific research that the solution of one problem only leads to another. Each discovery is but one more stepping stone in the march of scientific progress, and the definite evidence that light consisted of energy travelling in some form of transverse waves presented the still more difficult problem of the nature of the medium in which these waves travelled. This has proved indeed a difficulty, and it must be confessed that at the present time, after a century of research, we are but little nearer to any true understanding of the real nature ot the medium, if indeed there be any real medium at all, in which light travels. That light energy reaches us from the sun and the stars certainly seems to demand a mysterious "something" in which the energy can reside during its journey through space, and the nineteenth century physicists adopted the somewhat doubtful course of endowing this hypothetical æther with the attributes of a material substance and attempted to investigate its properties by analogy with the properties of material substances.

The two properties which an ordinary substance must possess in order to permit the transmission of waves are mass and the right type of elasticity to give it the power of resisting the displacement of its particles caused by the wave motion. A gas possesses what is called compressional elasticity—it reacts to any change of volume. Consequently it can transmit waves, such as sound waves, which, as we have already said, are a series of compressions

and rarefactions, the individual gas molecules vibrating along the line of travel of the wave—that is to say, a longitudinal wave. The transmission of a transverse wave involves a change of shape of the medium only, and neither a gas nor a liquid offers any resistance to a mere change of shape. Only solids possess this form of elasticity, which is known as rigidity. The "luminiferous æther," therefore, if it was to be likened to a material substance, had to be regarded as an elastic solid.

This elastic solid hypothesis led to many difficulties with which we need not concern ourselves. We need mention only one which has a special interest for us. It was that a vibration in an elastic solid should be propagated not only as a transverse wave but as a longitudinal wave as well, for an elastic solid possesses both rigidity and compressional elasticity. Now, no evidence could be (nor has been) found of any longitudinal wave in the case of light. Our interest in this lies in the fact that it was erroneously thought at the time of their discovery that X-rays might prove to be a manifestation of this longitudinal wave.

To meet this difficulty various modifications of the elastic solid theory have been proposed, such as regarding the æther as incompressible. The more the knowledge of the subject has increased the greater have become the difficulties that have beset the elastic solid theory, and many have been the speculations and hypotheses that have been advanced. Nowadays we no longer try to fit an æther to our own ideas of a material substance.

The first half of the nineteenth century brought still more problems to be grappled with, for during this period the necessity for yet another medium was realised in order to explain electrical phenomena. Faraday had discovered electro-magnetic induction and had introduced his revolutionary views by which the centre of interest in an electrically charged body was transferred from the charge on the body to the electric force in the medium surrounding it.

It was not long before Clerk Maxwell, inspired by Faraday's work, published his famous electro-magnetic theory. By skilful mathematical reasoning he was able to show that one and the same medium would suffice to explain both light and electrical phenomena and to predict the discovery of those electrical waves which we now know so familiarly as " wireless waves." He showed that they would travel with the same velocity as light waves travelling in a vacuum, and that, in fact, the two were identical, light waves being merely electro-magnetic waves of short wave length. Newton's visible spectrum was thus extended beyond the infra-red on its long wave length side by the whole range of electric waves, just as it has since been extended beyond the ultra violet, on its short wave length side, by the discovery of X-rays and the γ-rays from radium. The visible spectrum is thus seen to constitute but a very small part of one vast spectrum of electromagnetic radiation.

CHAPTER IV

EARLY X-RAY HISTORY

RONTGEN gave the first public account of his great discovery to the Physico-Medical Society of Wurzburg at the end of 1895 in a paper that must be regarded as noteworthy for its accuracy and the completeness of the author's investigation of the properties of the new rays. He described how barium platinocyanide is caused to fluoresce by the rays from a Hittorf or a Crookes or a Lenard tube, operated by a large induction coil, and that these rays would penetrate card, wood and thin sheets of metal. He had found that different metals possessed different transparencies and had compared the absorption of the rays in different metals. Lead of 1.5 millimetres thickness he found to be practically opaque. Glass containing lead was more opaque to the rays than glass that was free from lead. " Of special interest," he said, " is the fact that photographic dry plates are sensitive to the X-rays." He illustrated this point by exhibiting the first X-ray photograph of a hand and also the first radiograph taken through metal, which showed a compass card and needle enclosed in a metal case.

Rontgen observed that the new rays differed from kathode rays, since they could not be deflected by a magnet. His investigations indicated certain points of similarity to ordinary light. It is of course a well-known fact that a sharply defined photograph may be obtained by using a pinhole in the place of a camera lens, and this

is only possible because light travels in straight lines. Rontgen took photographs of his tubes in operation with a pinhole camera (made, of course, of metal, so that the rays could only reach the photographic plate through the pinhole) and obtained well-defined and undistorted pictures, thus showing that X-rays also travel in straight lines. Moreover, his pictures showed that the greatest quantity of rays emanated from the most brilliantly fluorescing part of the glass wall of the tube. That the glass or the fluorescence were not essential to the production of the rays he also showed by constructing a tube closed with an aluminium plate two millimetres in thickness on to which the kathode stream was directed. From this apparatus, which constitutes the first step towards the construction of a metal X-ray tube, he was able to obtain his rays just as with an all-glass tube.

It was obvious that in many respects the X-rays were very similar to ordinary light. Rontgen had, therefore, made careful comparisons of their properties. Light can be reflected by a suitable surface, but Rontgen could find no surface which would definitely reflect a beam of X-rays. It is interesting to note that, to prove this point, he passed the rays through finely powdered rock salt and also silver powder and zinc dust, and found the absorption of the rays the same as for the same thickness of material in the unpowdered state. If the rays were reflected he expected to find a difference, and he concluded that there was no regular reflection of the X-rays. Twenty years later, as we shall see in the chapters dealing with X-ray spectroscopy, it was found that something akin to reflection does take place at the faces of the tiny crystals in powders such as Rontgen used, but under the conditions of his experiments the reflections from all the crystals resulted only in a certain amount of diffusion or scattering of the rays. He concluded that "regular reflection does not exist, but that bodies behave to the X-rays as turbid

media to light," in other words, the rays are scattered as a beam of light is scattered in fog or in a cloudy liquid. Rontgen *did* find apparent reflection from pieces of certain metals placed beneath a photographic plate, but he concluded correctly that this was only another example of scattering.

Rontgen tried to refract his new rays by using prisms made of a variety of substances such as ebonite and aluminium, but without success. He also tried to obtain evidence of interference and polarisation of X-rays. Had he succeeded, there would have been little doubt left of their similarity to visible light, but his results were negative in both cases, and he was consequently led to put forward a different suggestion as to their nature, which appears in his original paper in the following words: " A kind of relationship between the new rays and light rays appears to exist; at least, the formation of shadows, fluorescence, and the production of chemical action point in this direction. Now it has been known for a long time that, besides the transverse vibrations which account for the phenomena of light, it is possible that longitudinal vibrations should exist in the æther, and, according to the view of some physicists, must exist. It is granted that their existence has not yet been made clear and their properties are not experimentally demonstrated. Should not the new rays be ascribed to longitudinal waves in the æther ?"

The first newspaper accounts of Rontgen's great discovery reached this country in the early days of January 1896, and a translation of his paper appeared in "Nature" a week or two later. The importance of the new radiation and the accuracy of Rontgen's investigation of its properties was at once recognised, but his suggestion that the long-sought longitudinal vibration of the æther had been at last discovered was immediately criticised. The theory of such longitudinal waves had been worked out long before, and Rontgen's suggested explanation of the new

rays was seized upon as a last hope by the upholders of the already dying elastic solid æther theory. J. J. Thomson now discussed their possibility from the point of view of the present discovery and the electro-magnetic theory. He showed that short longitudinal waves would not be refracted by ordinary media, but pointed out that short transverse waves also would not be refracted if their wave length were sufficiently short; so short, in fact, that it must be comparable with the distances between the molecules of ordinary substances. This early speculation as to the wave length of an X-ray has proved to be extremely accurate.

That these new rays were short wave length transverse vibrations similar to visible light very quickly became the general opinion of the physicists of this country. We may quote in particular the opinion of Professor Schuster, who at once pointed out that there was no conclusive evidence that the new rays were not ordinary light vibrations of very short wave length and that they behaved exactly as would be expected of such waves. He emphasised the difference between the new X-rays and kathode rays and regarded the magnetic deflection of the latter as conclusive proof that they were not a form of wave motion. As to the origin of X-rays, he suggested that possibly this was the vibration of the electron within the molecule instead of the molecule carrying with it that of the electron.

This suggestion is somewhat striking, because we must remember that at that time little was known of electrons and their existence was entirely a matter of theory. The actual existence of free electrons or of any particle smaller than an atom had not been recognised. The study of electrolytic conduction had suggested the idea of an atom of electricity many years before. When a current passes through a conducting liquid the molecules are split into two portions, which Faraday named ions and which travel in opposite directions through the liquid. Each ion is

found to carry with it a perfectly fixed and definite quantity of electricity, and the charge carried by the simple hydrogen ion was assumed to be one indivisible unit. Johnstone Stoney had given the name of "electron" to this atom of electricity. Lorenz, in 1878, had explained the properties of dielectrics (electrical non-conductors) by a theory of such charged particles or electrons confined within the molecules, and it was assumed that the charge in the particle was the same as that carried by the hydrogen ion. It was not until 1897, as we shall see in the next chapter, that the actual existence of electrons was demonstrated by practical experimental work.

During the weeks following Rontgen's announcement physicists all over the world were busily engaged in repeating his experiments and in examining the properties of the new rays. A great deal of discussion occurred at first as to the point of origin of the X-rays. The vacuum tubes in use were mostly of the type in which an unfocussed kathode stream from a flat kathode impinged on the glass wall of the tube, such as had been introduced by Crookes for showing the production of fluorescence under the action of the kathode stream. It was found that the fluorescent part of the glass was the source of the X-rays in tubes of this type, and this gave rise to the idea, which for a time was very general, that the fluorescence of the glass was necessary for the production of X-rays, in spite of the fact that Rontgen had shown, with his aluminium window tube, that neither the glass nor the fluorescence were essential. It was not long, however, before the true fact was realised that the X-rays arose from the point where the flight of the kathode stream was stopped. The first clear statement of this fact in this country appears to have been due to Professor Porter, who had worked with a Crookes tube in which the kathode stream was focussed on to a piece of platinum and who may, therefore, be regarded as one of the first users of the focus type of X-ray

tube, which in a few months supplanted all other forms of vacuum tube for the purpose.

Meanwhile, from all the intensive work which was being carried out on the new subject, at least one very important new fact had emerged. J. J. Thomson, at Cambridge, and Benoist, in Paris, both discovered in February 1896 that

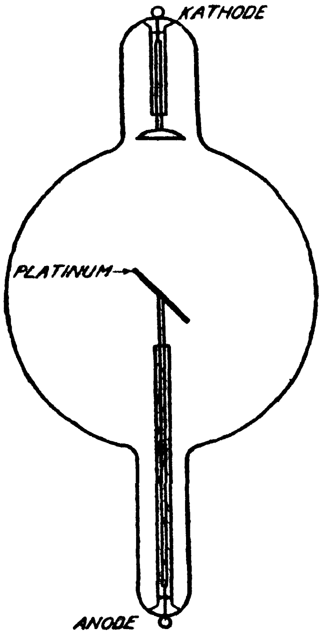


FIG. 6. EARLY FORM OF FOCUS X-RAY TUBE

X-rays would discharge an electrically charged conductor. Thomson suggested that the leakage of the charge was due to the splitting up or ionisation of the molecule of the surrounding air just as the molecules of a conducting liquid are split up in electrolysis, so that the charge was actually conducted away through the surrounding atmosphere. He also erroneously concluded that solid dielectrics, such as

ebonite or paraffin wax, were rendered conducting by the rays—a very pardonable error, caused by the fact that the scattering of the beam of X-rays produced ionisation and consequent leakage of charge in unexpected places. The fact that ionisation was only produced in gaseous dielectrics was recorded a month or so later by Professor Righi, of Italy. Thomson had also, in February 1896, studied the absorption of the rays in different substances and had discovered that X-rays are not all of the same kind. Actually, the rays coming from a tube are a mixture of rays of different wave lengths. Chabaud, in Paris, had measured the absorption of X-rays in various metals and found it increased with the atomic weight of the metal.

Many were the speculations and the theories put forward during these early months as to the nature of X-rays. Perrin, in France, had very early concluded, as had the British physicists, that they could not be a form of kathode rays, but as the nature of the kathode ray was still an unsolved problem this only rendered the question a little more complicated. In Germany, Rontgen's longitudinal wave suggestion was the most popular, although some German men of science dissented from this view. Goldhammer, for instance, believed, with the British school, that X-rays were ultra violet rays of extreme shortness of wave length. He suggested that the absence of refraction confirmed this view, since several theories of dispersion of ordinary light led to the conclusion that the refraction would become less and finally vanish as the waves became shorter. The absence of reflection he described as due to the roughness of all polished surfaces compared to the extremely minute wave length of the X-rays, an explanation which we now know to be correct.

In America opinion seems to have been divided. Tesla investigated the diffuse reflection or scattering of the rays from different metals and thought his results showed that

X-rays were streams of radiant matter. Professor Pupin, of New York, on the other hand, suggested that they might be found to be " a circulating motion of the æther, and that the stream lines are diffusely scattered within the molecular interstices of ponderable substances." He also suggested that the diffusion of X-rays so closely resembled Lenard's results with kathode rays that the two must be similar and that possibly the X-rays did experience slight deflection by a magnet, but that the effect was masked by the scattering.

Another American physicist, Professor Michelson, put forward yet another theory of X-rays. He rejected the longitudinal wave theory because of the absence of reflection and refraction. Considering the projected particle or radiant matter theory, it was difficult to see how the particle could pass so easily through the walls of the tube and yet to explain how the vacuum inside a tube could remain good for years. His own suggestion was that X-rays consisted of æther vortices (like smoke rings), forced out from between the molecules of the kathode by the intense negative charge. Like Pupin, he considered that X-rays and kathode rays were essentially the same, the X-rays being kathode rays which had been sifted out, as it were, by the material they had traversed.

All these suggestions as to the origin and nature of X-rays belong to the first half of the year 1896, and they give some indication of the uncertainty and the variety of the views at this period. New facts as to the properties of the rays were still being discovered—sometimes seeming to favour one theory, sometimes giving support to another. Professor Haga, of Gröningen University, and J. W. Giltay, of Delft, Holland, both found that, like visible light, X-rays alter the electrical conductivity of the element selenium. J. A. McClelland, of Cambridge, confirmed Thomson's earlier observation, that a beam of X-rays is not homogeneous, but consists of a mixture of rays. He

measured the relative transparency of glass and tinfoil by observing the rate at which the rays which passed through them caused an electric charge to leak away. If the rays passed direct from the tube to the glass or tinfoil he obtained a figure for this ratio different from the figure obtained if he first filtered his rays by passing them through some other substance. He concluded, correctly, that the filter cut out and absorbed some portion of the rays, but allowed others to pass.

A number of workers at this period thought that they had obtained diffraction effects by passing the rays through narrow slits in a manner analogous to the diffraction effects of visible light, and attempted to measure the wave length of X-rays by this means. Their results were entirely fallacious, for the amount of diffraction or spreading of the rays beyond the strict geometrical shadow is so minute in the case of waves as short as we now know X-rays to be, that it was entirely masked by the scattering of the rays from the air or from the edges of the slit.

There was one other event in the first half of the year 1896 of supreme importance to the development of physical science, to which we must now refer—the discovery of radioactivity by Becquerel. For some years there had been a great deal of interest in substances which fluoresced under the action of kathode rays and ultra violet light. The discovery of X-rays and the fluorescence produced by them gave a fresh impetus to the subject, with the result that Becquerel very soon found that uranium, or its compounds, constantly emitted radiations which were very similar to X-rays in that they would penetrate opaque objects, ionise gases and cause fluorescence. This was the first knowledge of the remarkable phenomenon of radioactivity, the study of which has contributed so much to our knowledge of the structure of the atom. Very soon it was found that the natural ores of uranium were far more active than uranium itself, and this led to the isola-

tion of the hitherto undiscovered element which was named radium, and also several other radioactive substances.

It was at first reported that refraction and polarisation of the uranium radiation had been observed, and radioactivity was, therefore regarded as a connecting link between X-rays and visible light, possessing some of the attributes of both, and was claimed by the wave theorists as lending support to their view of X-rays. Subsequently it was shown that these radiations from radioactive substances consist of a mixture of three types of radiation (distinguished as α, β and γ-rays) having vastly different properties, and although the γ-rays were found to be similar to X-rays of extremely great penetrating power, the comparison which was made in 1896 between X-rays and the mixture of rays arising from radioactive substances was fallacious.

It will be seen that the position in the latter part of the year was somewhat complicated. The kathode ray problem was still unsolved, the nature of X-rays was entirely problematical, and now there was added the entirely new and unexpected phenomenon of radioactivity to be investigated. As we have seen, the British physicists had very generally decided that the kathode rays were streams of radiant matter, and that X-rays were vibrations akin to light waves, but of shorter wave length, and consequently of greater frequency, although there was as yet no definite proof of these assumptions. The greatest difficulty with regard to X-rays was that they could not be polarised, but it was generally assumed that polarisation could be produced, if only the right means could be found. As J. J. Thomson pointed out, it had been found that the long electric waves can be polarised by passing them through a metallic grating like a wire birdcage, whilst the shorter infra red waves require a framework of very fine wires which would still be far too coarse to have any effect on

the waves forming visible light. Hence " it is likely that the structure of tourmaline, though fine enough to polarise ordinary light, may not be fine enough to polarise the Rontgen rays."

The fascinating story of the research into radioactivity we must leave. How the other threads in this somewhat tangled skein were unravelled we shall endeavour to show in the succeeding chapters.

CHAPTER V

"WEIGHING" THE ELECTRON

IT was not long before further progress was recorded. The following year—1897—saw the solution of one of the problems mentioned in the last chapter, for the nature of the kathode stream was settled beyond all reasonable doubt by the remarkably ingenious experimental work of J. J. Thomson in this country, and also by Wiechert and Kaufman in Germany.

Lenard had shown that the kathode stream was not only deflected by a magnet, but that it was also dispersed or spread out. A beam of kathode rays narrowed down by passing through a slit will, of course, produce only a narrow line of light on a fluorescent screen. Under the action of a magnet the rays are deflected, and so strike the screen in a different place, but the line is also broadened out into a band. This effect is very similar to the dispersion of ordinary light when it passes through a prism, and therefore became known as the magnetic spectrum. Birkeland, who, it must be noticed, used an induction coil to supply the electric discharge through his vacuum tube, found, on repeating this experiment in 1896, that his narrow line broadened out, not into one band, but into a series of lines. Now this is exactly analogous to the effect obtained when light made up of a mixture of a limited number of colours (or frequencies) is passed through a prism. Each frequency is refracted by a different amount, so that a series of lines results (known as a line spectrum) each line

representing a different frequency. Birkeland's result, which was really due to his induction coil, was so similar to the optical line spectrum that it was taken in many quarters as confirming the view that the kathode rays were a form of light.

The first step towards a true understanding of the kathode stream was made when J. J. Thomson succeeded, as we have already mentioned, in producing an electrostatic deflection comparable with the magnetic deflection. As has been explained, he brought his electrified plates close together inside his vacuum tube, and so obtained a vastly increased electric field between them, but he also worked with a better vacuum than the previous experimenters, so that there was less gas left in his tube. It must be remembered that what is ordinarily spoken of as " a good vacuum " is only a rarefied atmosphere—it is very far from being a perfect vacuum. The actual number of molecules of air or gas remaining in a vacuum tube, although small compared with the vast numbers present at atmospheric pressure, is still very large. The kathode stream passing through the residual molecules ionised some of them, and so, as it were, manufactured for itself an electrically conducting protective sheath which screened it from the electric field almost as effectually as a metallic sheath could have done. Thomson, by improving his vacuum and so reducing this ionisation effect, was able to examine the deflection of the kathode stream by the electric field.

And now came one of those brilliant pieces of scientific reasoning which, backed by experimental proof, form the milestones along the road of scientific progress. If the kathode stream really consisted, as still seemed probable, of flying particles of electrically charged matter, they must have a definite and measurable mass, the mass of a body being that property which we recognise when we weigh it. It was manifestly impossible to weigh these particles, but

there were now two measurements that could be made—the amount by which they were deflected by an electric force, the strength of which could be measured, and the amount of the deflection that could be produced by a magnetic force also of measurable strength. There were, then, two possible measurements and three unknown quantities, the mass of a particle, the electric charge it carried, and the speed with which it was moving. From these two measurements Thomson was able to obtain a relationship between the three unknowns. He was able to calculate the velocity and the ratio of the charge to the mass of a particle.

In Thomson's actual experiments he applied his magnetic field from the outside of his vacuum tube so that it would deflect the kathode stream in exactly the opposite direction to the deflection produced by the electric field between the two plates inside the tube. The kathode stream fell on a fluorescent screen mounted inside the tube, so that any deflection could be observed. Both the electric and the magnetic field were applied simultaneously, and their strengths so adjusted that their effects exactly balanced each other with the result that the spot of light produced by the kathode rays on the screen was unmoved.

The extremely ingenious (although mathematically simple) method by which the velocity of the particles and the ratio of their charge to their mass (usually denoted by e/m in which e represents the charge and the m the mass) were calculated will be found in any text book of the subject and need not be dealt with here. It was found that the velocity was very variable, even in the same discharge. An average value was about 3×10^9 (three thousand million) centimetres per second (nearly 19,000 miles per second), which is about one-tenth the velocity of light. The speed was found to vary with the nature of the discharge through the tube. Actually it depends upon the

voltage applied to the tube, the higher the voltage, the greater being the velocity of the kathode stream—a point which we shall see is of the greatest importance in the practical applications of X-rays.

The ratio e/m on the other hand was found to be always the same whatever the character or the voltage of the discharge, and for any pressure or degree of vacuum in the tube or whatever the nature of the residual gas or the metal of which the electrodes were made. Here then was a constant quantity which at once invited comparison with that other constant quantity to which we have already referred, the charge carried by the hydrogen ion in electrolytic processes. The quantity of electricity transferred and the mass of hydrogen associated with the transfer were measurable quantities, so that the ratio of the charge to the mass of the hydrogen ion was known, and it was also known, from the kinetic theory of gases, that each simple hydrogen ion represented a single hydrogen atom. Now the value of this ratio obtained from the kathode stream experiment was found to be many times greater than the same ratio for the hydrogen ion. Thomson's original figure, which was afterwards found to be lower than the true value, showed that it was at least 800 or 900 times as large. If the projected particle theory of the kathode rays was correct, then either e, the charge carried by each particle, must be very much larger than the unit charge associated with electrolysis, or else m, the mass of the particle, must be very much smaller than the mass of the hydrogen ion, that is to say, the hydrogen atom. The conception contained in this latter alternative was indeed a revolutionary one, for hitherto the atoms had been regarded as the ultimate and indivisible constituents of all matter. Thomson, however, quite correctly accepted this view and decided that the kathode stream consisted, as Crookes had suggested, of a flight of material particles, which he called corpuscles, very much smaller than the lightest atom

known and each carrying a unit negative charge of electricity and moreover, that these particles were common to all atoms.

Confirmation of these startling deductions of Thomson's was soon forthcoming, for in the same year Kaufmann measured the deflection of the kathode stream in a carefully arranged magnetic field and, by making certain assumptions, was able to calculate a value of e/m which later research has shown to have been remarkably accurate, and which he found to be always the same, whatever the conditions of the experiment. Then, too, Wiechert devised a clever method of making a direct measurement of the velocity of the kathode particles by means of an electric condenser discharge, the frequency of which could be calculated by the methods now so familiar to "wireless" engineers. He found, with Thomson, that the velocity was of the order of one-tenth of that of light, and that it depended upon the voltage applied to the tube electrodes. This result was important, because the difference of the velocity finally disposed of the idea that the kathode stream was a form of light vibration.

The radiation from the kathode of a sufficiently exhausted discharge tube was now shown to consist of negatively charged corpuscles of a smallness hitherto unimagined. Kaufmann's figures showed that their mass must be about $\frac{1}{1850}$ of the mass of the lightest atom, assuming their charge to be the same as the unit charge connected with the hydrogen ion in electrolysis.

Here, then, was the first experimental evidence of the actual existence of Johnstone Stoney and Lorenz's hypothetical electron, although there was as yet no actual proof that Thomson's corpuscles were the same thing. Fortunately the connecting link appeared almost immediately in the Zeemann effect, which had been discovered only the year before. If an element is volatilised and rendered luminous, either in a flame or by an electric discharge, the

light it gives out consists of a mixture of certain definite frequencies, or colours, characteristic of the element. If the light is analysed by a spectroscope it gives a line spectrum consisting of a number of lines, each line corresponding to a particular frequency. Now the Zeemann effect is observed when the flame containing the luminous vapour is placed between the poles of a powerful magnet. The spectrum lines are then seen to split up, forming three (and sometimes more) lines where there was one before. Moreover, the light forming these extra lines is found to be polarised.

An explanation of some of the effects observed by Zeemann was given by Lorenz very shortly after the publication of Thomson's work on the kathode stream in 1897. He assumed that the light vibrations given out by the luminous vapour arose from something which was oscillating, and, he argued, since it is effected by a magnetic field, that " something " must carry an electric charge. Lorenz worked out the effect of a magnetic field on oscillating charged particles and found that the frequency would be altered according to the direction of oscillation with respect to the magnetic field. He showed also that some of the components of the emitted waves would be polarised and that the direction of the polarisation would be reversed according to whether the particle was positively or negatively charged.

Now the direction of the polarisation obtained by Zeemann indicated a negative charge. It was, then, fairly clear that the source of the light must be that negative particle, the electron, which was now rapidly emerging from the regions of pure hypothesis. Lorenz, by measurements of the Zeeman effect, was able to obtain a value for e/m the ratio of the charge to the mass of the oscillating electron. It was found to be in close agreement with e/m obtained from the kathode stream, and the fact that the fundamental agent was one and the same, the electron in

both cases was thus established, and the modern era of electronic physics had begun. Many determinations of the value of e/m have since been made on moving electrons obtained from different sources, such as the β-rays of radium, electrons emitted by incandescent metals and so on; always, within the limits of experimental error, with the same result. The electron is everywhere the same, and e/m is a universal constant. Assuming, then, as there seemed good reason to suppose, that the value of e was the same as the charge associated with the hydrogen ion, the value of m was known—the electron had been weighed. It has been found to possess the extremely minute mass of about 8.9×10^{-28} grm.

And now we come to another beautiful piece of clever experimental work, which at once led to an understanding of the process of ionisation of a gas and at the same time justified the assumption which had been made as to the value of e. If very damp air is cooled a mist or cloud results and it had been known for many years that each individual water drop in the cloud is formed around a small particle of dust. In perfectly dust-free air the cloud will not be produced ; but C. T. R. Wilson made the discovery that if dust free air was ionised the ions would act as nuclei for the formation of water drops. He showed this by causing moist air enclosed in a glass vessel to expand suddenly. The expansion cooled the air and a cloud was formed so long as any dust was present. By forming several clouds in succession in the same atmosphere and allowing them to settle, the air was washed clean of dust, and no more clouds could be formed. If now this dust-free air was ionised, say, by allowing X-rays to pass through it, a small expansion would again produce a cloud, each individual water drop forming around an ion and therefore being electrically charged. Wilson showed that drops would form more easily and with less expansion around negative than positive ions. It will be realised that this method

actually rendered the individual ions visible in the form of water drops. Wilson has produced many beautiful and instructive photographs showing the production of ions in the track of a beam of X-rays, the radiations from radium and so on.

In 1898 J. J. Thomson used this experimental method to make the first measurement of the charge on a gaseous ion. By expanding ionised gas by just the right amount so that drops would form around the negative ions only and then allowing the cloud to settle, it was easy, by means of an electrometer to measure the total charge on all the ions in the clouds, but to find the charge on an individual ion it was necessary to know the total number of drops in the cloud. The seemingly impossible task of counting the water drops in a vessel full of fog was achieved by Thomson by an ingenious indirect method. These clouds were found to settle down steadily with a sharply defined upper edge, so that the rate of fall could be observed. The rate at which a small drop of water will settle down had been shown by Sir George Stokes to depend upon the radius of the drop. By applying Stokes' law the radius, and hence the volume of a drop, was obtained. The total volume of water in the cloud was ascertained when the whole cloud had settled down, so that dividing one by the other, the number of drops was known. The total charge had been measured so that the actual charge on each drop, that is to say, the charge on each negative ion, had been ascertained. Its value was found to be remarkably near to that old friend, the charge on the hydrogen ion in electrolysis, the value that had been assumed to be the charge on an electron. Equally important, the charge on a gaseous ion was found to be always the same, whatever the gas that was ionised or the method of ionisation.

There were many sources of uncertainty and possible error in Thomson's original experiment. Improved

methods based on the same fundamental principle were applied by H. A. Wilson, and later by Millikan, in America, who experimented with great care and accuracy. Both these investigators, by the methods they adopted, were able to observe and measure individual drops. Although they found that some drops had double or even treble the unit charge, the charge on any drop, either negative or positive, was always an exact multiple of the unit charge.

There could now be little doubt as to the identity of the negative ion. Once again there was the same unit charge independent of the nature of the gas from which the ions were produced. This could be no mere coincidence. The charge on a negative ion was identified with the electron, and it was realised that the process of ionisation was, as has been described in the first chapter, the splitting off of an electron from the atom. This identity of the electronic and the ionic charges did much to justify the assumption that had been made as to the charge on the electron. A little later Townsend was able, from experiments on the velocity and diffusion of ions, to give a direct proof that the ionic charge was the same for the ions of all gases and equal to the charge on the electrolytic hydrogen ion. Although much other confirmatory evidence has since accumulated, the matter was virtually settled. Thus, in less than two years the kathode stream had been explained, the electron had been experimentally discovered, weighed and its charge measured, and the mechanism of ionisation explained.

CHAPTER VI

X-RAYS IN PROGRESS

JUST before the publication of Thomson's work on the kathode stream Sir George Stokes introduced his famous spreading pulse theory of X-rays. A similar theory was also put forward independently by Wiechert at about the same time. It was by now well known that the X-rays originated where the kathode rays impinged on some solid obstacle ; that is to say, at the point at which the kathode rays were stopped. Stokes supposed that each of the kathode ray particles (they were still thought to be molecules) when stopped was the origin of a pulse of electromagnetic energy spreading out spherically from the point of impact of the particle, each separate particle sending out a separate pulse. This theory is important, because it is the explanation of the process of formation of an X-ray from the point of view of what is known as the " classical theory "—the theory of continuously spreading waves which was developed mathematically in such wonderful fashion by Clerk Maxwell on the basis of Newton's laws of dynamics. It had extremely valuable results, for it led, as we shall see, to very material progress in the knowledge of X-rays. It demands some explanation here, not only because of this, but also because of that modification of it known as the nucleated pulse theory, introduced some years later by J. J. Thomson, which comes so near to helping us to visualise some of the conceptions of modern physics.

The Stokes theory is based on Faraday's very useful conception of lines of electric force to which we have already referred on page 26. Each of the charged particles, or electrons, of which the kathode stream is composed is supposed to carry with it, either when it is at rest or when it is moving at a steady speed, its own system of straight lines of force radially distributed around it. Maxwell's electro-magnetic theory shows us that any change or disturbance cannot take place instantaneously in such a system, it can only travel at one speed, the velocity of

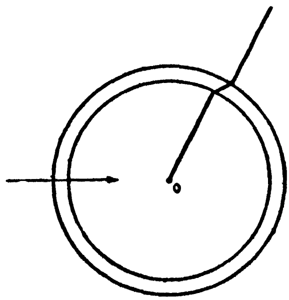


FIG. 7. REPRESENTATION OF FORMATION OF A " KINK " IN A LINE OF FORCE

light, which is the speed of all electro-magnetic disturbances. The lines of force possess inertia, that is, they require energy to change their motion.

If, then, one of the kathode stream electrons collides with an obstacle and is stopped, the effect of the collision takes a definite time to travel along the lines of force which are meanwhile moving on as if nothing had happened. The straight lines must become distorted, although they rapidly readjust themselves to their normal straight radial form after the effect of the shock has travelled on. The result of the collision is that a kink is formed in each of the lines, and is flashed outwards along it with the velocity of light. Figure 7 shows the formation of a kink

in a line by the stoppage of an electron originally moving in the direction of the arrow. It must be remembered that the electron is supposed to be surrounded by such lines spreading out from it in all directions. The diagram shows one of them only.

Each moving kink is virtually a short line of force flying radially outwards from the stopped electron. Moving lines of electric force carry with them a magnetic force, so that there is a pulse of electro-magnetic energy radiating spherically outwards with the velocity of light, forming a sort of spreading shell. The thickness of the shell (the space between the two circles in Fig. 7) depends upon the time taken to stop the electron, and that will vary with its original speed. The more rapidly it is stopped the closer together are the beginning and end of the disturbance—the thinner is the pulse. It is important to notice that a pulse is produced whether an electron is stopped or whether it is suddenly made to move, in fact, whenever its speed is changed.

There is one difference between this electro-magnetic pulse, which constitutes an X-ray, and light, in that we have here a single disturbance only, whilst the Maxwellian theory of light contemplates a succession of recurring disturbances forming a train of waves. But a little consideration shows that the same method will suffice to explain how a regular train of light waves may be set in being, for if we take the case of an electron that is not merely stopped, but is oscillating to and fro, so that it is constantly changing its speed, a succession of such pulses will be sent out, and these will form a train of waves. The slower the oscillations the thicker will be the pulses, so that the distance between successive pulses is greater. In other words, the wave length is longer. The thickness of the pulses formed by the comparatively slow speed changes of an oscillating electron will be much greater than the thin X-ray pulses, so that the spreading pulse theory

regards X-rays as being similar to light of very short wave length, and consequently of great frequency.

The theory as developed by Thomson (and elaborated later by Sommerfeld) was the first real attempt to form a rational and connected theory of the production of X-rays. It succeeds in explaining many of the facts and brings out several important practical points. For example, we see the necessity of a rapidly moving kathode stream if we wish to produce very penetrating X-rays, which are X-rays of very short wave length. The theory only fails, as we shall see a little later, where the whole Maxwellian theory also fails to explain some of the phenomena of radiation in general.

This intermittent pulse theory of X-rays did not receive acceptance in all quarters, particularly among the German physicists. The proof of the corpuscular nature of the kathode stream had given some support to the advocates of the materialistic view of X-rays, especially as the hitherto unimagined smallness of the particles made the penetration of solid matter appear more feasible. B. Walter, in 1898, published in Germany the opinion that X-rays could be regarded as kathode particles which had lost their negative charge. This would account for the fact that they were not deflected by a magnet, and he suggested that it would enable them to penetrate the solid walls of the vacuum tube more easily than the charged kathode particles. The theory is interesting as a forerunner of the corpuscular theory introduced by Sir Wm. Bragg nearly ten years later. It was somewhat negatived, however, by some experiments reported at the same time by another German physicist, J. von Geitler, which proved that, although X-rays could discharge two opposite electric charges by rendering the air between them conducting, they were quite incapable of conveying a charge from one place to another as a flight of material particles should certainly be able to do.

It will be realised that scientific opinion was not at all agreed at this time as to the nature of X-rays. New facts as to their properties were gradually discovered, but, far from providing a proof of any one of the theories that had been suggested, they only served, as we shall see, to render the question more involved.

The next piece of new knowledge of the properties of X-rays came from France. Perrin had been experimenting on the production of ionisation in gases and had been using an ionisation chamber—a simple piece of apparatus consisting of a closed vessel to hold the gas, with two metal plates inside it, between which the conductivity of the ionised gas could be measured. He had noticed, in 1897, that there was a very considerable increase in the ionisation produced by the X-rays if the beam of rays was allowed to fall on to either of the metal plates, and that the amount of this effect varied for different metals. This was obviously connected in some way with the scattering from metals which Rontgen had recorded.

Sagnac accordingly, early in 1898, undertook a very complete investigation of the scattering of X-rays. He at once observed that they are scattered by all substances, even by the air through which they pass—a fact which had already been noted by Rontgen. He found that metals produced a transformation of part of the original rays, for the scattered rays included rays which were less penetrating than the original or primary rays. These transformed rays became known as secondary rays. The penetrating power of the secondary rays was found to depend on the metal. From the heavy metals the secondary rays were found to be very mixed in their nature, a part of them having such low penetrating power as to be absorbed by only a few millimetres of air. He also discovered that when the secondary rays fell on to metal they again gave rise to a new scattered radiation—tertiary rays.

It was suggested that the differences observed in the

secondary radiations were due to differences in the surface conditions of the metal from which they were scattered, but J. S. Townsend proved, in 1898, that this was not so, and that they really came from the substance of the metal. Moreover, he showed that the very easily absorbed portion could be made to travel greater distances by reducing the air pressure. In the following year Sagnac and Curie, by producing secondary rays in a vacuum, discovered that these easily absorbed rays were very different from the X-rays which gave rise to them, for they carried with them a negative charge, leaving the metal from which they were radiated charged positively. Then almost immediately Dorn found that they could be deflected by a magnet. This easily absorbed radiation was, therefore, like the kathode rays, of a corpuscular nature, a radiation of material particles negatively charged. In the next year, Dorn, by measuring the magnetic deflection, found that these negative corpuscles were emitted from the metal with a speed of about 10^9 cms. per second, a velocity very similar to the velocity of the kathode stream electrons. It was now fairly evident that this "radiation," like kathode rays, consisted of electrons. The explanation of the speed at which they are emitted forms one of the problems of modern physics.

We now know that when X-rays encounter any substance, part of the radiation is scattered unchanged (or almost unchanged), as these early experiments showed, much as light is scattered in a fog. Of the unscattered part, some passes straight on unchanged, but some is absorbed, and it is the energy of this absorbed part which is responsible for the appearance of what were known as secondary rays. These are now understood to consist of a mixture of electrons ejected from the absorbing atoms and "characteristic" rays, which are X-rays less hard* in

* X-rays of high penetrating power are spoken of as "hard" rays and easily absorbed X-rays as "soft."

quality than the primary rays which have given rise to them. Their actual quality depends upon and is characteristic of the atom producing them. At the period with which we are dealing the existence of this transformed radiation had been experimentally observed, as we have seen, but characteristic radiation as such was not discovered until some years later.

For the next few years no fresh experimental facts came to light. The centre of interest was now the method by which the X-rays became scattered and transformed into secondary rays. A theory of scattering was worked out by J. J. Thomson as a development of the spreading pulse theory and published in 1903. He supposed the scattered rays to arise from sudden changes of motion—that is say, an acceleration—of the electrons in the atoms of the scattering substance, the changes being induced by the X-ray pulse as it passes over them. If it were a light substance, in which the atoms and electrons were a good distance apart (compared with the thickness of a pulse), each electron would be affected just so long as a primary pulse was passing over it, and would therefore become the source of a secondary pulse of just the same thickness as the primary. This would represent simple scattering.

The theory showed that when X-rays traverse a thin layer of material the scattered rays should be most intense along the line of travel of the primary rays, but equally distributed on both sides of the layer—the forward scatter and the backward scatter should be equal, and this should be so whatever the hardness of the rays. Experiment showed that the theory was only partially correct and that when hard rays were used the forward scattering was very much in excess of the backward. We shall find that this fact has to be taken into serious consideration when the question of the future possibilities of the practical application of X-rays is discussed.

Thomson's theory led at once to a very important

development—the discovery of polarisation of X-rays. It regarded the scattering from light elements as due to a simple acceleration of individual electrons, such as the case considered in our simple " kink " diagram. Now it can be shown mathematically that the energy in a spreading pulse is very intense in directions at right angles to the original line of movement of the electron and that it becomes gradually less in directions approaching the line of movement along which there is no energy radiated at all. If this theory is right, then the rays scattered by the light elements should have a maximum intensity in one plane gradually diminishing to a minimum intensity (or zero intensity) in a plane at right angles to it. In other words, they should be polarised.

Here there came a serious practical difficulty—the difficulty of finding a suitable light substance to scatter the rays. Gases were obviously the most suitable, but the scattered radiation from them was too feeble. However, it occurred to Barkla, who was energetically working at this problem, that the primary beam from an ordinary X-ray tube must be at any rate partially polarised. The kathode stream electrons are all travelling in the same direction, so that if they were all stopped at their first encounter with the target we should have again the simple case of our theory, and the resulting rays should certainly be a maximum in one plane. If, as is actually the case, some of the electrons are deflected when they strike the target, and collide with several atoms before they are stopped, the polarisation would be only partial. Barkla, by a careful examination of the intensity of the radiation in different directions, was able to show polarisation of both the primary and secondary rays, the latter being, as was expected, very much more completely polarised than the former, a result which he first published at the University of Liverpool in the early part of the year 1904.

It is probable that if polarisation had been observed

some years earlier, say, in 1898, the fact would have been generally accepted as proving the similarity of X-rays and light. The question was now not quite so simple, for the fresh knowledge of the properties of the rays gathered in the last previous years had brought into prominence several facts which were extremely difficult to explain. What, for instance, was the explanation of the high speed of these electrons which had been found to be given off from a metal surface when irradiated by X-rays ? According to the spreading pulse theory, the energy of an X-ray is derived solely from the energy of the kathode stream electron which gives rise to it, and this energy travels outwards in an ever-spreading sphere. It is quite clear, then, that only a small fraction of the original energy can travel over any one point. The total energy of a pulse is being spread out over an ever-increasing area as it travels outwards. Nevertheless, it had been found that this continually weakening pulse could liberate electrons from a piece of metal and send them shooting off at a speed which showed them to possess energy comparable with the whole energy of the parent kathode stream electron.

It is not surprising that it was suggested that the energy of the liberated electron came from the atom from which it was ejected rather than from the X-rays, for the recently discovered phenomenon of radioactivity had been shown to be due to a disruption of atoms. It was thought for a time that X-rays had the power of acting as a trigger which could bring about a sort of explosion of certain atoms. C. H. Wind, in 1907, suggested that the X-rays obtained their energy not only from the kathode electrons but also from the atoms of the target against which they struck, a theory which was by no means adequate to explain all the facts.

Another source of difficulty was concerned with the ionisation of gases by X-rays. The number of ions produced in a gas by a beam of X-rays had been measured

experimentally and had been found to be absurdly small (a proportion of something like 1 to 10^{12}) compared with the number of molecules in the path of the rays. Why should an electron be knocked off one molecule and millions of other similar molecules remain unaffected? It might have been supposed that the affected molecules were those which were already in rapid motion, that is to say, those that possessed special amounts of kinetic energy; but if this were so, the temperature of the gas should affect the ionisation, for increasing the temperature of a substance increases the motion of its constituent molecules. Perrin, and later McClung, showed that the amount of ionisation was quite independent of the temperature.

The liberation of electrons from a metal surface by X-rays was in itself a significant fact, because it had been known for many years that ordinary light, and in particular ultra violet light, could cause the emission of electrons —photo-electrons they are termed—from a clean metal surface. Lenard had, shown in 1902, that although the number of photo-electrons produced varied with the intensity of the light, the velocity with which they were emitted was quite independent of the intensity; and when Barkla found, in 1906, a similar result with X-rays, another strong argument was provided for the similarity of the two phenomena. In the following year P. D. Innes found that the velocity of the electrons depended on the quality, that is to say, the hardness, of the rays producing them, and on that only, the velocity being the same from any substance for rays of the same quality.

Although these results certainly indicated the similarity of X-rays and light, consideration of the energy acquired by the electrons rather led to the conclusion already mentioned, that they resulted from atomic explosion, the rays or the light merely acting as a trigger which in some way caused the electron to be ejected from the atom by its own inherent energy. As an alternative there was another

possibility to be considered—the possibility of the atom storing up energy from the successive X-ray pulses passing over it until it had acquired sufficient energy to eject its electron. This was an attractive hypothesis which appeared to provide a simple explanation until the actual quantities of energy involved were investigated, and then it was found that the time required for a particular atom to store up the requisite energy would be enormous if the energy were only conveyed to it in accordance with the spreading pulse theory, whereas in actual fact there was a practically instantaneous emission of electrons from a few atoms and none at all from others. The storage of energy hypothesis, therefore, would not fit in with the experimental facts, but, on the other hand, if the energy was derived from the atoms themselves, why should the amount of it vary with the quality of the ray which caused its release, and why should it be independent of the nature of the atom? The spreading pulse or wave theory of X-rays had thus led science into an awkward dilemma, and if the truth of the theory was to be established, some means of explaining the concentration and localisation of the energy was clearly necessary.

Consideration of these difficulties and the extent of the discrepancy between theory and experiment, led Sir W. H. Bragg (then Professor Bragg) to take the bold step of discarding the generally accepted theory of X-rays and resuscitating the corpuscular ideas of their nature in a new and extremely ingenious theory of neutral pairs, which he first described to the Royal Society of South Australia in May 1907. He supposed an X-ray to consist of a negatively charged particle—an electron—to which was closely attached a similar but positively charged particle, the resulting pair being, therefore, electrically neutral. From this starting point he was able to account for most of the known properties of X-rays. He showed that the hardness or penetrating power would depend upon how closely the

two particles were bound together. On striking against an atom a pair might rebound unchanged, or the two particles might be partially or completely separated, thus accounting for scattered and secondary radiation. Polarisation was supposed to be due to a rotation of the neutral pairs, but it must be said that the theory was not completely successful in explaining the polarisation of scattered radiation.

A corpuscular theory of this type certainly made it easy to explain the localisation of the energy effects at particular points, but the greatest objection to the neutral pair theory was that it necessitated the assumption of a positively charged particle having a mass small compared with the very small mass of the negative electron, a conception without any experimental basis and unknown in any other physical theory. Nevertheless, a long controversy ensued, chiefly between Bragg and Barkla, who adhered to the spreading pulse theory, and the clever neutral pair theory was not finally abandoned until several years later, when, as we shall shortly see, the actual production of interference phenomena with X-rays left no doubt of their similarity to light.

Barkla's work of the past few years had now led him to the definite recognition of the existence of that form of secondary radiation characteristic of the atom emitting it to which we have already referred. In 1908 Barkla and Sadler were able to show that every element emits its own characteristic X-ray, which is always of one definite quality or hardness, when X-rays of the same or harder quality fall on it. They were led to this discovery by making careful observations of the absorption of rays of different qualities. Measuring the absorption in, say, a piece of copper, they found that it became steadily less as the hardness of the rays increased, but that this went on only up to a certain point, when a still further increase of hardness produced a sudden *increase* in the absorption.

This was accompanied by the emission from the copper of X-rays just a little softer in quality than the rays which had been absorbed. These rays were found to be absolutely characteristic of the copper, for when the primary rays were made still harder they did not change—their quality remained just the same. The same thing happened with any element, each element having its own characteristic radiation of its own particular quality, which is produced whenever X-rays of the same or slightly harder quality fall on it. Barkla was able to show two characteristic radiations from many elements which he called K and L radiations, the K radiation being always very much harder than the L radiation. Characteristic radiation is always accompanied by the emission of electrons. In fact, the former, as we shall see when we come to consider the wonderful knowledge that the study of X-rays has given us of the inner structure of the atom, is really the indirect result of the latter.

" Hardness " or penetrating power we now know to be merely a matter of wave length, the hard rays being those of short wave length. The characteristic rays were thought to be of uniform hardness (in contrast to the rays coming from an X-ray tube, which consist of a mixture of a great number of different wave lengths). They are often spoken of as homogeneous, or, from the analogy to ordinary light, as monochromatic radiation. Again, from the fact that they are caused by the transformation of a ray from a short to a slightly longer wave length, they are analogous to the phenomenon of fluorescence obtained with ordinary light and are sometimes referred to as fluorescent radiation. More recent work (on X-ray spectra) has shown that these characteristic rays are not really homogeneous, but consist of a mixture of two or three groups of wave lengths of very nearly the same magnitude.

The knowledge of how to produce X-rays of approximately uniform quality was of the greatest assistance in

experimental work, and enabled Sadler and Beatty to confirm and amplify the researches of Innes and others. A few years later, in 1912, Whiddington showed, from Beatty's results, the striking fact that the speed of the electrons ejected from a substance, whenever its characteristic radiation is produced by shooting sufficiently hard X-rays on to it, is not only surprisingly high, but is actually the same as the speed at which the kathodal electrons must travel in the X-ray tube in order to excite that particular radiation. Thus the whole energy of an electron was shown to be transferred, by means of the X-ray it produced, from the tube to some point, perhaps many yards distant, and there handed over intact to another electron.

Here was the same energy difficulty once more. The spreading pulse theory was based on the Maxwellian theory of light and assumed the similarity of X-rays and light, but clearly it was not sufficient as it stood to explain all that was happening. Moreover, the ionisation of gases by ultraviolet light, and, as we have seen, the study of photo-electrons, was resulting in just the same difficulties in explaining the transfer of energy in the form of light as in the form of X-rays. To many physicists, then, the problem was now becoming one of finding some modification of the Maxwellian theory which would explain the observed phenomena of both X-rays and light rather than to deny their similarity, as did Bragg's neutral pair theory.

An attempt to solve the problem on these lines was made by J. J. Thomson, in 1908, when he introduced the modification of the Stokes pulse theory, which became known as the nucleated pulse theory. He imagined each electron, instead of carrying with it a whole system of radial lines or tubes of force, to be possessed of one tube only, and that the result of any change of the motion of the electron travelled out along that single tube of force, an X-ray pulse being, as on the older theory, a single disturbance due to a single sudden change of motion and a

light wave being a train of periodic disturbances produced by oscillation of the electron. The energy travelling along the tube would depend upon how sudden was the change of motion of the electron ; that is to say, on the thickness of the pulse, so that it would be always the same for the same frequency (or wave length). An increase of intensity of the radiation simply means that more tubes of force are crowded together in the same space, each electron sending out the same amount of energy along its own tube so long as the frequency is unaltered.

This theory certainly made it easy to see how the whole of the energy could be almost instantaneously transferred from an electron to a distant molecule which happens to lie in the path of this concentrated pulse, and it also assumed and explained the similarity of X-rays and light which now seemed so probable. There was one big fact against it, however. It could not explain diffraction and interference, of ordinary light, and in this respect it failed as completely as Newton's corpuscular theory had failed a century earlier. For X-rays the case was a little different, for these phenomena had not been observed with any certainty. Haga and Wind (and also Sommerfeld) had indeed obtained results with diffraction experiments, from which they claimed to have calculated the wave length of the X-rays employed, and had arrived at a figure (1.3×10^{-8} cm.) which cannot have been far from the truth, but their results were not generally accepted. Thus the similarity of light and X-rays was still regarded as unproved and even, in many quarters, as improbable.

An important change was now coming over this problem. The work of the past few years in all branches of physics had brought out the fact that this energy problem was not confined to the study of X-rays or light, but was fundamental to the whole theory of radiation. We have shown here the difficulties which arose and something of the way in which the older theories failed to explain

them. With that, for the moment, we shall leave the energy question. In a later chapter, where we shall recapitulate and amplify the more important points that have been touched on here, we shall deal with those revolutionary ideas of radiated energy which were first introduced by Prof. Max Planck and elaborated by Einstein and others.

Starting from Planck's new theory and with the knowledge of the mass and speed of the secondary X-ray electrons, Wien was able in the year 1907 to calculate what should be the wave length of an X-ray pulse. He arrived at a value of the order 10^{-9}cms., and Stark in the following year reached a very similar result.

It was now becoming fairly clear that the wave length of X-rays, if they had a wave length at all, that is to say, if they were not material particles, must be round about this figure. Now, the wave length of visible light can be measured by means of a diffraction grating, which, as was explained in Chapter III, is ruled with 20,000 to 40,000 lines to the inch, that is, lines spaced out at distances comparable with the wave length of the light. But the wave length of visible light was from 4,000 to 8,000 times as large as these estimates of X-ray wave lengths, so that to construct any diffraction grating fine enough to be capable of dealing with such short waves was obviously a a mechanical impossibility. However, it occurred to Prof. von Laue, of Munich, that there was a possibility that nature had supplied that delicate structure which could not be made by human means. He suggested that the atoms of crystals, which were believed to be built up of regularly arranged atoms spaced out at distances of the order of 10^{-8}cm., might act as a diffraction grating for X-rays. The problem was not quite so simple as that of the diffraction of ordinary light, for a crystal would form a three dimensional grating—a pile of single layer gratings in front of each other—but Laue worked out the theory of

the subject (from Maxwellian principles) and showed that if a narrow beam of X-rays passed through a crystal a number of diffracted beams, arranged symmetrically around the central beam, should result. The actual experiment was tried in the early part of 1912 by Friedrich and Knipping with immediate success. The well-known work of Profs. W. H. and W. L. Bragg followed immediately. They showed that interference could be produced by "reflecting" the rays from the various planes of a crystal which are most rich in atoms. To this important work and the vast developments which have arisen from it we shall return in a later chapter.

The work of Laue removed all doubt as to the nature of X-rays. The definite production of interference at once swept away the corpuscular theories and showed that X-rays were, after all, but light of very short wave length. The problem of the transfer of energy was and still remains unsolved.

CHAPTER VII

X-RAYS AND THE ATOM

NOT the least romantic chapter in the history of physics is concerned with the fundamental unit of matter which was called by the ancients the Atom. Two or three thousand years ago the physicists of the time had their atomic theory. It formed an essential part of the philosophy of Aristotle and it supplied the poet Lucretius with an immortal theme. The conception of the atom has suffered certain vicissitudes during the ages, but it is a remarkable thing that the theory of Thales the Greek, who lived six hundred years before Christ, that all forms of matter were really different manifestations of a common, or fundamental, substance, has now become the prevailing idea. Matter is now thought to be a manifestation of electricity; and the modern view concerning the atom and its constituent parts is entirely based on the conception that electricity is in fact a material thing. It is a number of infinitely small granules which are quite invisible and which always will be invisible even when the most perfect microscope is used.

When we consider that modern scientific resources have enabled us to know with absolute exactness the number of these granules in any particular atom, and further to know how much they weigh, and probably how they move, we realize the romance of scientific investigation and the genius of the great investigators.

The modern view concerning the atom is based on the

theory of the physician William Prout, who at the end of the eighteenth century assigned weight and definite character to certain atoms. Prout held the opinion that hydrogen was the ultimate unit of matter and that all atoms were made up of these particular units. The question of the atom in its relation to chemical compounds was also considered by the chemist Lavoisier, whose work resulted in the enunciation of the famous law of the conservation of mass—which says that matter can neither be created nor destroyed; in other words, it was shown that the weight of a chemical compound was the sum total of the weights of its constituents.

The development of the atomic theory is also associated with the work of the chemist Dalton, who showed that atoms differed from one another in nature and weight; and by means of analysis of compounds he was able to assign an atomic weight to some atoms. Taking hydrogen as unity, the weights of other atoms were expressed as multiples of this. Dalton then proceeded to form pictures of chemical combinations by associating different atoms, and so producing a compound atom, or, as we now call it, a molecule. The "compound atom" of Dalton was not always correct, but nevertheless it formed the basis of modern chemistry. The discovery that some elements had *fractional* atomic weights was a great blow to the prevailing theory that hydrogen was the fundamental unit of all atoms, and it is only quite recently that the brilliant work of Aston has clearly explained this apparent anomaly. He showed that it is possible for certain so-called elements to have precisely the same chemical properties and yet to be made up of atoms having a few different weights. Such elements were called Isotopes by Professor Soddy, who first remarked on them, having deduced their existence from radioactive considerations. It may be that the theory that hydrogen plays some essential part in the very nature of matter is right after all.

Although from the time of Dalton the atom, possibly the hydrogen atom, was regarded as the ultimate unit of matter, there were, from time to time, hints forthcoming from certain speculative men of science that a still smaller unit was really at the bottom of it all. Such a unit, the electron, first received a name from Dr. Johnstone Stoney. We have seen how the proof of the existence of this important unit has revolutionised the whole of scientific thought. About the middle of the nineteenth century Sir Edward Frankland, as a result of a study of the manner in which atoms combined with each other, introduced the important term *valency*, which described the particular affinity possessed by atoms for certain other atoms. Study of the combining ability of atoms was very general about this time, and led to the first definite arrangement of the known atoms in the order of their atomic weights. This work culminated in the construction of a table of the elements by the Russian chemist, Mendeléeff, in 1863. Recent work has shown that in this table certain elements appear at regular periods which have curious characteristics. They will not combine with any other atoms ; Argon, Neon, Krypton, Xenon are examples. They are known as the inert gases. Moreover, the elements in the immediate vicinity of these inert gases in the periodic table are observed to resemble each other in their properties consistently as they occur through the table.

From what has been said, it is clear that towards the end of the nineteenth century a vast amount of information had been collected concerning atoms and their chemical behaviour, but it was not until 1897 that the real advance in knowledge came. Professor J. J. Thomson made the truly epoch making discovery that the kathode rays discovered by Hittorf in 1869 were really isolated electric charges having a definite mass, the value of which, as we have seen, he was able to determine. This discovery

went far to revolutionize current views concerning the nature of electricity.

The position with regard to the atom was by this time very much altered—it could now be said that we knew of the electron as the smallest known expression of mass, and, further, the work of Townsend and others had shown that atoms contained electrons, because they were actually knocked out when a gas was ionised. It remained to find out how these electrons were arranged to form atoms. It was obvious that, in general, the atom was electrically neutral ; at the same time one of its constituents, the electron, had been shown to be a negative electric charge. How then was the necessary compensating positive charge arranged in the atom ? Many speculations were put forward. It was obvious that the atom was of such a nature as to allow the passage through it of swift electrons, because Professor Lenard had shot them through aluminium foil the thickness of which contained thousands of atoms. Sir Ernest Rutherford was at this time experimenting with a product of radioactivity known as alpha particles, which are really atoms of *helium* ejected at tremendous speeds from a radioactive material ; alpha particles, which are really atoms of helium ejected at these particles were scattered or deflected by matter in the course of their flight. By means of a suitable fluorescent screen he was able to observe little splashes of light which were caused by the impact of these particles, and by shooting them at atoms he was able to deduce the fact that the atom consisted of a loose structure, having a very massive and positively charged central nucleus or sun. Most of the alpha particles fired at the atom passed through it without having their velocity or course altered at all, indicating that nothing comparable in mass to the alpha particle itself had been encountered ; hence the probable general emptiness of the atom. On the other hand, occasionally an alpha particle was seriously deflected, or even, in some

instances, actually turned back on its track. It had evidently met something of a mass comparable or greater than itself, the influence of which repelled or deflected its passage. As the energy and the mass or charge on the alpha particle was known, it was possible by observing the angle of deflection to calculate, by the interposition of certain assumptions, the charge on this massive constituent of the atom.

By shooting alpha particles at different atoms (in the form of metal foils) and by observing and measuring their deflections, Rutherford was able to calculate the amount or number of the positive charges in any atom, and it was very remarkable that the number of positive charges so calculated appeared always to be approximately equal to half the atomic weight of the atom.

As a result of this work Rutherford postulated an atom, consisting of a small massive and positively charged nucleus surounded by a sufficient number of electrons to balance the positive charge on the nucleus, the whole structure being loose and resembling a planetary system. This development carried us a long way further in our efforts to visualise the atom, but apart from some work done by Professor Barkla on the scattering of X-rays by atoms, X-rays had not so far played any essential part in the advance of atomic knowledge. In 1913, however, a young English physicist—Moseley*—carried out some brilliant investigations of supreme importance, both from the point of view of X-rays and also atomic structure.

We shall see in a later chapter that some time after the discovery of X-rays a method was developed by which an X-ray beam could be deflected by a crystal and its component wave lengths separated out into a spectrum, enabling the frequency of each constituent wave to be measured. Very soon after, the method was used to confirm the fact

*Moseley lost his life in the great war. at Gallipoli

that X-rays could excite atoms to emit radiation—the X-radiation, in fact, which was characteristic of the atom. It was recognisable by perfectly definite and characteristic lines which appeared on a suitably placed photographic plate.

Moseley used various elements as the targets of his X-ray tubes, and with consummate ability he measured the wave lengths of the characteristic X-rays which were emitted by each different element. He found that the frequency of these characteristic radiations were related to one another in a very curious and simple way. Instead of obtaining close relationship with the atomic weights of the elements, the X-ray frequencies were related by the simple numerical series 1, 2, 3, 4, etc. Moseley assigned to each element its appropriate number, which he designated the "atomic number." Hydrogen was 1, Helium 2, Lithium 3, and so on, forming a regular unit staircase. He was quick to recognise that he had discovered something of much more fundamental importance than atomic weight. The "atomic number" is, in fact, indicative of the actual number of unit free positive charges on the nucleus of the atom, and is the one factor which governs its chemical properties. It means that the hydrogen atom has one positive charge on its nucleus, and therefore it has one compensating electron arranged somehow outside. It means also that if we could find a means of attaching three extra positive charges to the hydrogen nucleus, two of them being neutralised by association with two extra nuclear negative electrons, also an extra compensating electron outside, thus leaving the nucleus with a net positive charge of two it would no longer be hydrogen, but helium. Transmutation of the elements!

The atomic number of the element lead is eighty-two. If we could knock out three positive charges from this nucleus and three external electrons, we should have realised the dreams of the alchemist, for the result would

be gold, the atomic number of which is seventy-nine. There are ninety-two elements, all in a sequence and progressing up the scale by the addition of one net positive charge to the nucleus. As we have seen, the table begins with hydrogen with one positive charge and one planetary electron, and the next is helium with two net positive charges and two planetary electrons. The eighth is oxygen with eight, and the last is Uranium with ninety-two positive charges and ninety-two planetary electrons. Two of the elements in the list have not yet been discovered. Two, numbers forty-three and seventy-five, were quite recently discovered by Noddack and Tacke, and were named Masurium and Rhenium respectively, and still more recently Illinium, number sixty-one, was discovered by an American investigator. The method by which these new elements are identified is by measuring their characteristic X-ray frequencies, for by the pioneer work of Moseley, although there may be a gap in the table of elements, the wave length can be predicted, even though the element itself has eluded search and remains undiscovered.

The mass or weight of an atom is concentrated in the nucleus. It may be regarded as the total weight of *all the positive charges*, which, by the way, are sometimes spoken of as positive electrons and sometimes as protons. The weight of the negative electrons is so small that it may be disregarded in comparison.

We have spoken of " free " positive charges in the nucleus, and in indicating our meaning we may explain why the atomic number is so often half the atomic weight. The nucleus of an atom is thought to contain not only a definite number of free protons, which determines its atomic number and constitutes the value of its positive charge, but also about an equal number of protons, which are bound in association with negative electrons within the nucleus. So that we have in one atom a certain number of protons, about half of which are neutralised by constant association

with a negative electron within the nucleus. The other half of the total number of protons are also within the nucleus, but in a *free condition.* It is the number of free protons in the nucleus that is equalled by the number of *planetary* electrons *outside* the nucleus. The total number of protons give the *atomic weight* of an atom, and the total number of *free* protons (often about half) give the *atomic number.* The discovery of the atomic number is probably one of the most striking scientific advances of modern times, and is due to the use of X-rays as an Aladdin's lamp in the hands of the wizard Moseley.

The vast amount of information now available concerning the nature of the atom led to speculations concerning its actual form and character. The hydrogen atom we know contains a nucleus of one positive charge and one planetary electron. It is probable that this planetary electron is revolving in an orbit around the nucleus. It was to be expected, therefore, that if it radiated energy in the course of this revolution, it would approach nearer and nearer, until finally it would actually fall into the nucleus, and that the atom of hydrogen would consequently cease to be. Neither of these things, however, does happen ; the hydrogen atom persists as a hydrogen atom, and it does not emit radiation at all unless its normal condition is altered by some external agency. Some other explanation of the structure and behaviour of the hydrogen atom is therefore necessary.

We shall see in the next chapter that a new energy hypothesis was introduced about 1900 by Max Planck and by its application to the consideration of the atom Professor Niels Bohr, of Copenhagen, was able to devise a most ingenious atom model, which satisfies many of the demands of the modern physicist.* The element first con-

* The various theories concerning atomic structure are admirably set forth in Professor E. N. da C. Andrade's book, "The Structure of the Atom."

sidered by Bohr was hydrogen, because of its relative simplicity. He made the primary assumption that there were many orbits in which the electron could revolve, but in the normal condition only one particular orbit is used, and the electron remains there until forcibly ejected, and also that in the normal state the atom

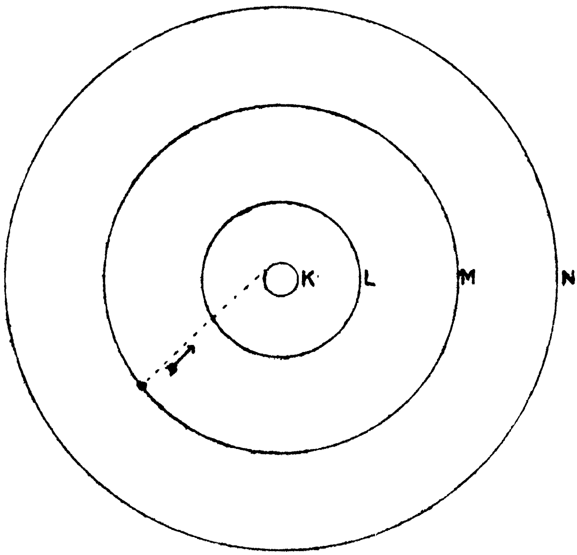


FIG. 8 DIAMGRAMMATIC REPRESENTATION OF CRYSTAL PLANES

does not emit radiation. If, however, the electron were to change from one orbit to another, the amount of energy which the atom possesses would also change ; and it would either have to deliver some up or acquire more by reason of the change. Upon this idea Bohr built up his complete theory of the structure of the atom. We will assume for the moment that in the hydrogen atom the planetary electron has a choice of four orbits, K, L, M, N (*see* figure 8). If it is circulating in orbit M, it will have more energy than it would require in orbit K, and should

anything occur to cause a change from the one orbit to the other to take place, it would be necessary that the excess energy should be given up. This delivery of energy takes the form of radiation, which is emitted by the atom. Its frequency or wave length is governed by the difference in energy possessed by the two orbits involved in the electron change. On the other hand, let us suppose that the electron is revolving in orbit K and is caused to change to orbit N. In this case it must acquire *extra* energy. It is not accompanied by the *emission* of energy by the atom but by its *absorption*.

Now let us consider how these changes of venue on the part of the electron are brought about. We have referred to the work of Moseley, who measured the X-ray spectrum lines of the various elements. How do these fit in with Bohr's theory of the atom ?

It is found, for example in an X-ray tube, that if any element is bombarded with electrons which have energy imparted to them by means of an electric potential the result is the emission of X-rays. The X-ray wave length depends upon two things—the atomic weight of the element bombarded and the energy of the electron. This, again, depends upon the electric potential. As the voltage is increased the minimum wave length of the resulting heterogeneous beam of X-rays is decreased. If we consider the reason for these happenings we shall see that the atom and radiation are absolutely interdependent. To refer again to Figure 8. The maximum amount of energy that could be lost by an electron would be if it were to drop from outside the atom into the very innermost orbit. Now, it is only possible for an electron to enter an inner orbit of the atom if there is *room* for it. What happens in an X-ray tube, for example, is this : A bombarding electron comes along at a terrific speed (imparted to it by the voltage applied to the tube). When suddenly stopped by the atom, it delivers up its energy and so causes an

electron to be ejected from one of the atom orbits. The particular orbit affected depends upon the speed or energy of the electron and upon the particular kind of atom. If a heavy metal like tungsten is used as the target in the X-ray tube, a voltage of 69,000 volts is necessary to impart the requisite speed to an electron to enable it to deliver up enough energy when it is stopped to eject an electron from the *innermost* orbit of the tungsten atom. We have already seen that this energy is absorbed by the atom, and, as a result, out goes an electron, *leaving room for one* in the innermost orbit. Incidentally, as the atom has lost a negative charge it is not now electrically neutral. It is positively charged and therefore abnormal ; and will tend to revert to its normal condition. An electron will fall from an outer orbit to take the place of the one which was ejected, and in so doing the atom will lose energy, which will be radiated from it as a characteristic X-ray of definite wave length. The X-ray in the case we have instanced will be the most penetrating one that the particular atom is capable of radiating. If the voltage is less than 69,000 volts, the electron will not have sufficient energy to effect the ejection of an electron from the *innermost* orbit, but perhaps only from the M orbit, and when *its* place is taken by another one the loss of energy will be much less and will result in the radiation of an X-ray of much less energy or lower frequency ; or, in other words, a much less penetrating X-ray. In addition to X-rays which are characteristic of the metal of the target, other X-rays independent of the target are produced.

When any X-ray target is bombarded by electrons, the fact that they are all moving with different speeds and are therefore stopped at various rates, when they hit the target, results in the production of X-rays of all frequencies. We say that the resulting beam of X-rays is heterogeneous.

For any particular element, however, certain critical

electron energies, due to certain definite voltages, cause the ejection of electrons from particular orbits ; as for example we have seen that electrons are ejected from the innermost orbit of tungsten at 69,000 volts. For platinum the necessary voltage is 78,000 volts, and gold 80,000 volts. This characteristic radiation may be so analysed as to produce intense spectrum lines on a photographic plate, which are superimposed on the blackening due to the general radiation.

The X-ray frequency may be measured by the distances from a centre point to these lines, and the frequencies are an index, as we have seen, of the orbits involved in the electron change in the atom. A photographic plate so exposed and exhibiting these lines is known as an X-ray emission spectrogram.

By virtue of the energies involved, the origin of X-ray spectra are confined to the inner orbits of the atom, but by using disturbing agencies of less energy than high-speed electrons, ordinary light spectra may be obtained. These are very much more complicated and are outside the scope of this book ; they only involve the outer orbits of some atoms, but atomic structure may be investigated and illustrated in exactly the same way.

It is to be noticed, as we shall see in the next chapter, that the electron does not move gradually or continuously from one orbit to another, but does so in definite jumps. If the energy of the disturbing agent be ever so little short of the amount required to eject an electron from a particular orbit, nothing happens. It must exceed a definite value. The steps in which energy manifests itself in its dealing with atoms of matter have been shown to have values dependent only on the frequency involved and on an invariable factor known as Planck's constant, to be referred to later.

CHAPTER VIII

REMARKS ON ENERGY

In order to clarify our views concerning the development of the theory of X-rays, and to follow modern scientific investigation into their nature and use, it becomes necessary to spend a little time in consideration of present day conceptions of energy of which X-rays are such an important expression.

Until recent years, the term energy was only commonly used in a comparatively restricted sense. It was often customary to speak of " force " where now we speak of " energy." Electric Force was a common expression in a wider sense than it is now used ; for example, Faraday contemplated the transmission of Electric Force. Incidentally it was Faraday who first suggested that electricity had a material character and postulated something very like the electron as its unit. Before Faraday there was a very virile theory which regarded electricity as a fluid ; but it was a curious fluid inasmuch as it had no physical properties !

Now-a-days it may be said that the whole science of physics is occupied in examining and trying to understand the various transformations of which energy is susceptible. The various manifestations of energy as regards big systems has been found to fit, with great accuracy, into what we call the classical theory of Newton and Clerk Maxwell.

In Chapter III we have seen that wave motion in all its common expressions may be explained by this theory.

Energy transformation is an everyday experience in our lives. A tramway system is useful because of its energy of motion which is derived or transformed from the electrical energy supplied by the dynamo at the power station, which in turn is transformed from the heat energy of coal which may be said ultimately to derive its energy from the sun. Although the classical theory has explained so many important observations concerning wave motion, it has never led to any satisfactory explanation as to the manner in which radiant energy is transmitted. We know that we do receive light and heat from the sun, and we know that these forms of energy have definite characteristics ; but the substance or medium which *conveys* the energy to us has never been understood, even though it has engaged the attention of philosophers for centuries.

It is true that the luminiferous æther was invented by Huygens as a medium for wave motion on the principle that if light was to be regarded as a series of regular disturbances, then obviously something must be disturbed. The notion of the light bearing æther became very general. It was an essential part of the theory which regarded radiant energy as continuous. With the advent, however, of the modern view, that radiation is *not always* a continuous phenomenon, the conception, or at any rate, the nature of the all prevading æther is a matter about which there is considerable doubt. Energy is unquestionably transmitted from one body to another, but we are still completely in the dark concerning the manner of its passing.

The adherents of the æther theory have sometimes been forced to endow the æther with attributes which appear to be utterly at variance with human experience, although in order that it should function in the required manner, these somewhat outré characteristics would appear to be essential.

In spite of the intellectual difficulties involved, the conception of the universal æther has provided the basis

upon which very valuable scientific work has been done. The continuous wave motion theory of Newton and Clerk Maxwell was universal and almost undisputed for some time after the discovery of X-rays, and as we have seen in a previous chapter, it was the failure of many X-ray manifestations to conform to it which caused such confusion regarding their nature.

It must be remembered that Clerk Maxwell's and Newton's laws were formulated as a result of the observation of the behaviour of large physical systems: for example the falling of apples, and the rotation of the earth round the sun. When X-rays were discovered, and we had to follow this new manifestation in its meanderings through atom worlds, we found that the laws to which we were accustomed did not explain the amazing happenings which were found in the realms of the infinitely small.

We have already seen how the phenomena of interference and electric waves fitted most beautifully into the current system of thought, but when X-rays were discovered, we were at once faced with their most recalcitrant behaviour. It might very well be imagined that the physicist had at last really invaded the domain of the metaphysician, having discovered perhaps some expression of underlying reality. It is as well to recapitulate some of the difficulties presented by the behaviour of the new rays. By their passage through a gas, they ionised it, but not at all in the manner that was to be expected according to the classical theory. If they were regarded as sweeping through it by ever spreading spherical waves, it was reasonable to suppose that the ionizing influence should have been communicated to all or nearly all the atoms in the gas, but this was not so. J. J. Thomson showed that of all the energy which was inherent in an X-ray beam, only a very small proportion was accounted for by the ionisation produced. Instead of a large number of the gas atoms being affected, only very few were ionized. It was evident

that in this respect X-rays did not appear to have the same energy distribution over the wave front that was commonly assigned to ordinary light.

When X-rays fall upon a body, they may cause the emission of electrons. The electrons so ejected depart with enormous speeds, something of the nature of 10^9 centimetres per second. This property of X-rays was an aspect illustrating their somewhat contrary behaviour; for in this they showed themselves as behaving in exactly the same way as ordinary light, which also causes the emission of electrons from some metals. At a somewhat later date it was shown that these electrons were emitted with velocities that depended upon the *quality* of the incident radiation. This fact again was the same as had previously been shown to be true of ordinary light.

If the incident radiation, either light or X-rays, was very intense, that is, present in great quantity, then the electron emission would be copious; but for a given *quality* of light, the intensity, or the proximity of the source, had no effect whatever on the *speed* of the emitted electrons. It will be noticed that this fact is contrary to what was to be expected according to the inverse square law. Now the speed of the emitted electron we have referred to, is an expression of its energy. We called it kinetic energy. We may express it in symbols as $\frac{1}{2}\, m\, v^2$ m being its mass and v its velocity. From the phenomenon just described, it is clear that before the light or the X-rays were allowed to fall on the particular material, the electrons were " bound " in the atom and they remained where they were. They must, therefore, have acquired extra energy in some manner due to the action of the radiation. Moreover the amount of energy so acquired bore a very definite relation to the kind of radiation involved.

Although in this particular case X-rays behaved exactly in the same way as ordinary light, yet in both cases it is light *invading the province of the atom* and in

some way imparting its energy to the granules we call electrons.

It had been suggested that perhaps the action of the light or X-rays falling upon a metal, had in some manner touched a trigger which had the effect of freeing an electron which went off with a speed entirely due to energy which was inherent in itself. This explanation, however, did not cover the extraordinary fact that if blue light were used, the speed of the resulting electrons was much less than it was when violet light was the exciting cause. For a given metal the speed of the electron was always the same for any particular quality of light. Another curious experimental fact strongly supported the idea that energy was actually delivered up by the radiation to the electron. If an X-ray of definite frequency or quality were allowed to fall upon a substance and eject an electron, thereby causing it to depart with a definite speed, and if this particular electron were suddenly stopped by an atom, then that atom would emit an X-ray of identical quality with the one which originally freed the electron. It appeared that no energy whatever would be lost by such a transaction. There is still another very interesting aspect of the emission of electrons due to radiation falling upon a body. It was found that although light of a definite quality would cause the phenomenon, other light produced no effect at all. If we tried a certain metal with light, say beginning with red, and gradually trying others progressively along the spectrum towards blue, we should find that one particular colour and all colours above it, would eject electrons : in other words, for any particular metal, electrons are freed by the action of light only when it attains a definite minimum frequency, and further, the higher up the spectrum we proceed, the greater will be the speed of the ejected electrons.

This fact did not at all fit in with the classical theory. Let us now consider something as a well known example

which does conform to it. We know that if we expose a chop to a gas griller, that within certain limits, it will get hotter and hotter depending upon the length of time we leave it there. In other words, the radiant energy, known as heat, will produce a gradually increasing effect. Now consider how surprised we should be if after placing the chop under the griller *nothing happened to it at all* until we turned the gas tap to a certain fixed position, when the chop would instantly change from a completely cold to a completely cooked delicacy. This analogy, however, conveys a rough idea of what happens in the case of emission of electrons by X-rays or light. If light of the wrong colour, or of a frequency that is too low, were to shine on a metal until doomsday, it would not cause any electrons even to crawl out. It was the consideration of such anomalies as these which made it impossible to find a place for X-rays in the conventional system of thought, where continuity and regularity of behaviour displayed themselves so consistently. The tiny, though stupendous vista, which had burst upon experience by the discovery of the electron, seemed to carry in its train phenomena demanding a complete reorganization of physical law.

In the year 1900 Professor Max Planck, as a result of the study of other forms of radiant energy, was led to make the remarkable and revolutionary suggestion that radiant energy is *not continuous*, but rather that it appeared that atoms give up, or radiate energy, in jumps of definite amounts ; in other words that radiation is *discontinuous*.

In his original paper, Planck assigned the radiating atom itself as the source of discontinuity and did not regard it as having anything to do with energy transmission. The work of Planck was concerned with investigating *atoms* and in observations of their relation to the continuous spectrum of radiation, and it led him to conclude that there was no such satisfactory relation on

the basis of existing views. The atom was not like a fire which sheds a genial and constant source of comfort through the room, but rather like an intermittant Vesuvius which, when stimulated, spits out energy in lumps. It was discontinuous phenomena which ultimately proved Planck's idea, but a most interesting and epigramatic observation was made some time ago by Professor E. N. da C. Andrade in the course of a lecture,—that Planck discovered discontinuity, not in discontinuous phenomena, but in the continuous spectrum.

Some few years after Planck's announcement, Einstein, as a result of some considerations of the photo-electric effect, carried Planck's conception a little further, but in a modified form. At the same time he showed how it was that the classical theory of energy transmission failed to explain electronic emission. Einstein showed that, apart from the work necessary to extract the electron from the atom, the kinetic energy possessed by an ejected electron was numerically equal to the frequency of the invading radiation multiplied by a constant.

What is known as Einstein's equation may be written :

$$\tfrac{1}{2}mv^2 = h\nu$$

where ν is the frequency and h the necessary constant.

Now this particular constant was found to have exactly the same numerical value that Planck had calculated for the pulses of energy emitted by atoms. We have seen, in the photo-electric effect, that electrons are only emitted when the exciting radiation has a definite minimum frequency. Einstein established a very definite relationship between radiation frequency and electron energy. If we symbolise the definite minimum frequency required to eject an electron by ν_0 and the actual frequency of the exciting radiation by ν, then we may write Einstein's equation as follows :

$$\tfrac{1}{2}mv^2 = h(\nu - \nu_0)$$

It was, therefore, shown by Einstein that in order to establish the relationship between the electron energy and the incident radiation in the photo-electric effect it was necessary to use this mysterious h as a factor, and that when this was done the energy transmission could be exactly equated.

Einstein differed from Planck in assigning the discontinuity to the energy itself, which he said went about in corpuscles, or packets, or quanta as they are called, each of value $h\nu$.

The same relationship applies to electrons when they are freed from atoms by X-rays, and so explains the system of line spectra. The hypothesis of energy packets has been applied to many varied physical phenomena and the numerical value of h has been independently determined by different experimental methods. The results obtained exhibit quite a remarkable agreement. The presence of Planck's h would seem to be essential in understanding any process involving the absorption or emission of energy by atoms.

The notion of discontinuous energy packets of definite value affords an explanation of many of the X-ray difficulties that we have mentioned. For example it explains why so very few of the atoms in a gas are ionised by the passage of an X-ray, and also why this number is much increased if the atoms are packed more tightly together, as in a dense gas.

We must now imagine little packets of energy travelling through the gas, not like ripples on a stream ever spreading outwards and onwards as the Clerk Maxwell theory demands, but like bullets. Sometimes they will hit an atom and sometimes they will not. When they do, they may knock out an electron and so ionise the atom—but very many will pass through without any electronic encounter at all. The notion also explains why the power of the radiation to ionise does not decrease with the distance from its

source as the little energy packets which constitute it, retain their character and size all through their life, and deliver it up intact whenever and wherever they are completely absorbed.

The hypothesis of Planck and Einstein means that perhaps we must revert to the views held before 1800 and regard light as corpuscular, at any rate as having sometimes a corpuscular character. It certainly would appear that when radiation has any dealings with matter it does so discontinuously. If, however, we can imagine an energy system not involving matter, but where energy proceeds unmolested as a sort of endless stream, we may be thrown back upon the older æther theory or possibly upon some form of the still older philosophical conception of substantia of the schoolmen!

Many efforts have been made to reconcile the quantum theory with the classical wave theory, for it appears very certain that the quantum has come to stay. These efforts so far have not been successful; and the explanation of the apparent contradictions involved is one of the outstanding problems of modern physics.

Some further work done by that very ingenious experimenter, Compton, in America, has modified our views concerning the inviolability of the quantum. It will be remembered that matter is composed of atoms which in turn are aggregates of electrons and protons. In the normal state we have seen that the electrons are held, or as we say "bound" within the atom. There are, however, in most materials a certain number of free or wandering electrons. In fact their presence confers very important properties. Now it has been very wonderfully shown that although an atom may absorb a certain energy quantum and that as a result an electron may be emitted with a definite velocity, yet it seems that an electron can only acquire energy in this way when it is "bound." In other words, it seems that a "free" electron is incapable of

absorbing the radiation energy of the quantum with which it is confronted.

If we assume that light energy is in fact conveyed in quanta or packets, we may imagine that a collision occurs between a quantum of light and an electron. What will be the result? Newton's classical laws of motion govern the circumstances of a collision between two *material* bodies. The lighter one loses some energy; in other words, it will get the worst of the encounter!

Let us assume that the light quantum and the electron behave as material bodies. It may be calculated that the mass of the light quantum is very much less than that of the electron, and therefore, if it can be shown that the light quantum does lose some of its energy in such an adventure, *but still proceeds on its way* with less energy—or we may say with lower frequency, then obviously its *total* energy has not been absorbed. It has not been annihilated. This was what Compton showed. He demonstrated, and his results have been confirmed by others, that when a light quantum collides with an electron it may not suffer annihilation as a result, but may still live. It may have another character or survive as light of *another colour*. It tends to change for example from blue to red.

Remembering this let us consider the photo-electric effect for a moment, where we saw that the *whole* of the energy of the invading light quantum was transferred to the emerging electron, and was exactly accounted for by the amount of energy the electron could be shown to possess. This fact obviously involves the complete extinction of the invading quantum. It does not survive in any character. The result of these particular experiments involves us in considerable difficulty. It means that even subatomic phenomena sometimes obey the classical laws; whereas at other times we are faced by the necessity of adopting the new idea of discontinuous energy packets introduced by Planck. If the energy of a quantum is not

completely absorbed, then it would appear that Newton's laws are applicable.

X-rays are light of infinitely small wave length. Their power is exercised in the realms of the infinitely small—hence the importance of the quantum in their connection.

X-rays are produced by the stoppage of electrons by matter; their frequency or penetrating power depends upon the deceleration of the electrons. In an X-ray tube this deceleration is largely governed by the voltage which is applied to the terminals of the X-ray tube. For any given voltage the resulting X-rays will have a limiting maximum frequency. This voltage is known as the *quantum voltage* and the maximum or limiting frequency of the X-ray spectrum as the *quantum limit.* Obviously therefore, we may define X-ray frequency in terms of voltage or alternatively in terms of electronic velocity. In fact we may speak of any one of these manifestations merely as a *quantum* which term is sometimes used by the French physicist, de Broglie, interchangeably.

CHAPTER IX

X-RAYS AND CRYSTALS

In addition to the fact that X-rays may be used to illuminate the interior of an atom and so allow the investigation of its complex structure, they may also be used to light up the interior of that hardly less fascinating body, the Crystal. Before we consider this new manifestation of the usefulness of X-rays and all that it means both to X-ray progress and science generally, we must try to understand exactly what we mean by a crystal. It is a word very common in every day use and it conveys the idea of something that has a brilliant sparkle, and this suggests that perhaps its inside may conceivably be very beautiful. We now know that it is; and we have to thank X-rays for the knowledge. The perfection of regular and beautiful lace work inside the crystal is truly exquisite. Most materials are crystalline. Many at once give the impression of their crystalline character by their appearance, but on the other hand many do not. It will come as a surprise to some people to be told that cotton and silk are crystalline whereas glass is not. Substances which are not crystalline are called amorphous. Crystals grow. It is possible to watch this growth by a very simple experiment. All that is necessary is to put a little drop of a solution of common salt and water on a thin piece of glass and quickly warm it. The water will evaporate and the salt will be left. It will be deposited as very beautiful feathery crystals.

What is a crystal? It is the *regular* aggregation of a

number of tiny complete units. The regularity of the arrangement of these units causes the crystal to be bounded by a number of plane faces which may reflect light and so cause it to sparkle. A crystal has perfect geometric form. Like all material things it has three dimensions and, therefore, has three axes along which the little crystal units arrange themselves like regular rows of bricks. The little units themselves have six sides arranged in three parallel pairs. Their sides may be equal or they may be unequal. The angles they make with each other again may be equal or they may be unequal. If they are equal and all right angles and the sides are all equal the result, of course, is a cube, and in fact this particular form characterises a great many crystals—for example, nearly all the metals crystallise in this cubic form.

So much for the external form of a crystal. It has been exhaustively studied for nearly two hundred years. The various types have been classified and reclassified. The various axes have been measured and related to each other, and the relationships have served to name the various systems to which any particular crystal may be assigned. The important thing for us to notice concerning this old science of crystallography is that all its data are derived from the *external form* of the crystal, together, perhaps, with some speculation concerning its internal economy. It was not until some time after the advent of X-rays that, by the genius of von Laue, they were used as a torch with which we could explore the interior, not only of the crystal, but also of the little crystal units themselves, and thus supplant or extend the speculation of the crystallographers and the chemists by actual scale models and accurate measurements.

Let us for a moment endeavour to obtain a little clearer knowledge of the crystal unit to which we have referred. It is the complete essence of its substance. It contains atoms and molecules. Having been formed by the

joining together of certain molecules in a characteristic manner it joins itself on to other similar groups of molecules and so goes on piling itself up with great regularity until such time as it is big enough to be seen—perhaps only with a microscope. When such an arrangement is capable of being seen we call it a crystal. Alleged amorphous substances may also consist in aggregates of regularly piled unit bricks, but they are not recognised as crystals, because for some reason the little units stop adding themselves together regularly before the aggregate is big enough to be seen. Now how many molecules does the little unit contain ? It contains the minimum number that gives character to the substance. For example, consider the substance quartz, which is an arrangement of the chemical called silicon dioxide. The molecule of silicon dioxide contains one atom of silica and two atoms of oxygen. Now it has been shown that it requires three molecules of silicon dioxide to confer the character quartz. Therefore each little crystal unit of quartz contains these minimum three molecules.

It must be remembered, therefore, that all through the solid structure of any crystal we have these little complete units of the substance *regularly* piled in three directions, and consequently forming a regular network. If we consider any point in one of these little bricks—for example,

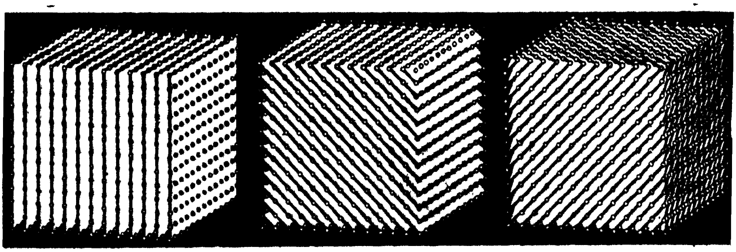


FIG. 9. DIAGRAM OF CRYSTAL REFLECTING PLANES

the centre of a group of atoms—such a point will regularly recur throughout the crystal and, with reference to it, we may draw a lattice which, viewed from any place about the crystal, will be apparent as such and through it we may draw a large number of planes. The illustration, Fig. 9, which appeared some time ago in " Engineering," shows how such planes exist relatively to a system of regularly arranged units.

It was said just now that the aggregates of crystal units are only recognised as a crystal if they are big enough. This is because ordinary light can only appreciate things if they are commensurate in size with the wave length of the light itself, because in order to be visible a body must reflect light. It is very easy to imagine the existence of things that are smaller than the wave length of light, many thousands of times smaller, in fact so small that the light wave passes over them and is entirely undisturbed by doing so. Now atoms and molecules and crystal units are such tiny bodies, hence they could never be detected by any ordinary optical system.

In 1907 a physicist named Wien determined that the wave length of X-rays should be round about 6.75×10^{-9}cms.—in other words that it was some ten thousand times shorter than the wave length of visible light. This fact was of the greatest importance because it directly led to the establishment of the true nature of X-rays, a matter about which there had been years of controversy. X-rays had very obstinately refused to allow themselves to conform in some respects to ordinary light phenomena. By the use of a diffraction grating, that is, a surface upon which thousands of lines were ruled at extremely close and regular intervals (about the same spacing as the wave length of light), it was very easy to analyse ordinary light. Such a diffraction grating, however, had no effect at all on a beam of X-rays.

The fact that X-rays had this wave length led Professor

von Laue in 1911 to suggest that perhaps a crystal, which was thought to consist of regularly arranged atoms, might be used as a natural diffraction grating for X-rays. It was a mathematical conception, but its experimental verification was at once attempted by Friedrich and Knipping with the most triumphant result. The atom spacings in the crystal were found to be of exactly the right order of magnitude and X-rays were at last found to be comparable in their behaviour with visible light. This was the crucial experiment which absolutely determined the nature of X-rays and identified it with ordinary light. The experiment was a comparatively simple one. A very narrow beam of X-rays was allowed to fall on a crystal behind which was placed a photographic plate. The result showed a central spot due to the main X-ray beam and in addition a number of spots arranged in a pattern, each spot marking the imprint of an X-ray pencil which was in fact a component of the main beam which had been deflected by a suitably placed atom plane within the crystal.

Here, then, in X-rays we had a form of light suitable, by reason of its minute wave length, for the investigation of such tiny entities as atoms, molecules and crystal units. The difficulty was, however, that the new light was not visible and methods had to be devised of appreciating its effects. The boundless possibilities involved were very soon recognised by Professors W. H. and W. L. Bragg, who were very soon able to show that a definite relationship existed between atom arrangement, X-ray wave length and the angle of the deflection of the rays. Consequently if two of these factors were known, it was very easy to obtain a knowledge of the third by a simple calculation.

Professor Bragg designed an instrument, which he called an X-ray spectrometer, by which these factors could be observed with great accuracy. It was so arranged that a fine beam of X-rays of known wave length was

allowed to fall upon a crystal mounted in such a way that by revolving it all possible crystal planes would have the opportunity to reflect the rays. The instrument was also provided with a means of recording the angle the reflected ray made with the main beam, and also of measuring its intensity.

It is a point worthy of notice that in the first experiments of Friedrich and Knipping they used a crystal as a *transmission* diffraction grating. The X-rays *passed through* the crystal and were deflected in the course of their progress. It was W. L. Bragg who first conceived the idea of using the crystal as a *reflection* grating. The use of this word " reflection " in connection with X-rays does not imply the same phenomenon as ordinary light reflection, as, for example, by a mirror. This is entirely a *surface* effect. Now there is no surface that could possibly be smooth enough to reflect X-rays. X-ray reflection takes place beneath the surface and is a function of the atom layers.

The method of spectrum analysis adopted by the Braggs was the first and most important use of X-rays in the investigation of crystals. Any crystalline material may be subjected to rigid analysis by this method with the result that all the properties of the material, for example, its hardness, toughness, brittleness, lubricating power, elasticity, and so on may be fully explained by the manner in which the inter-crystalline atoms are arranged. In the next chapter, we shall consider some of the practical ways in which these analyses have been of value in scientific progress and industry. The other most valuable use of the Bragg spectrometer has already been mentioned. If we know all about the crystal, if we know how its atoms are arranged and have measured the distances separating the atom planes, we may use the spectrometer to analyse a beam of X-rays of unknown wave length. It will be remembered that this is what Moseley did when he was able

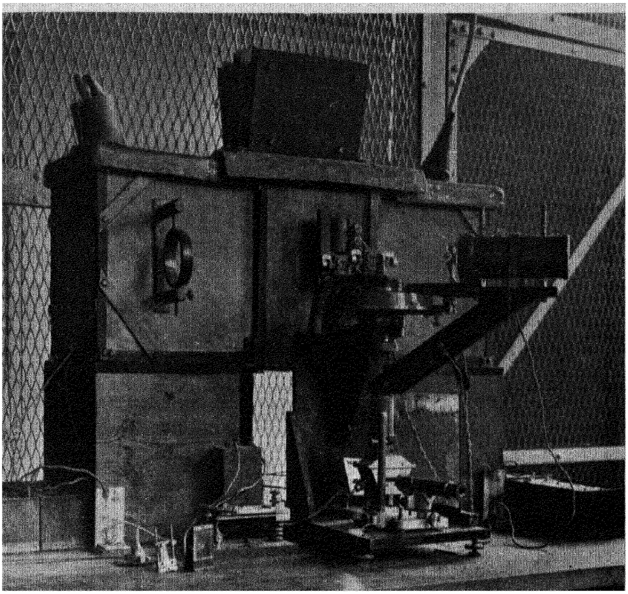


FIG. 10. BRAGG X-RAY SPECTROMETER INSTALLED IN THE RADIOLOGICAL LABORATORY. WOOLWICH

to show that the elements bore such a simple relation one to another.

The inspiration of von Laue and the brilliant development of X-ray spectrum technique by the Braggs had indeed put a mighty instrument into the hands of the scientific investigator. It is almost impossible for us to form any idea of what its ultimate value will be. If we think that all our experience and knowledge has been acquired in the past because, owing to light, we have been able to see things, we may now regard ourselves as having just been endowed with another light, potent in another world, which is full of new phenomena and so far practically unexplored but, nevertheless, as full of wonders as the big material world in which we move.

Following upon the work of the Braggs, other methods of X-ray spectrum analysis have been developed. The Bragg method originally employed a single crystal in the X-ray spectrometer and in order that every possible atomic plane might be investigated it was necessary that the crystal should be revolved.

This technique imposed certain limitations on applications involving the study of some crystalline substances. One condition necessary was that the crystal under examination should be fairly large. It had to be big enough to allow of a certain amount of manipulation. Furthermore, in order to interpret X-ray results and to correlate them with other known properties of the crystal, it had to be sufficiently developed or grown to enable its main axes to be determined. These conditions meant that crystalline substances which could only exist in the form of very minute crystals were not suitable for X-ray spectroscopic investigation. These considerations led to the use of an alternative technique which was developed by Debye and Scherrer and independently by Hull. It is known as the powder method. Instead of a single crystal, the powder method employs a mass of tiny crystals all

jumbled up into complete irregularity or chaos. In order that every possible reflecting plane in the crystal powder shall contribute its quota to the resulting diffraction pattern great care is observed to grind the crystal into very fine powder. It is then placed in a tiny glass tube and a beam of X-rays of known wave length is allowed to pass through the mass, and the result is a very beautiful pattern on the photographic plate. It consists of a series of concentric rings. The explanation of this pattern is really very simple and it affords a striking illustration of the power of these incredibly small atom planes to proclaim their existence in an unmistakable manner. Among the complete chaos to which they have been reduced, some will be arranged at the one possible angle suitable to reflect this particular wave length of X-rays—very much as some ripples on the sea, but not all, are at a suitable angle to reflect the moonlight with such charming effect. If we think of a number of these little atom planes disposed at the proper angles and reflecting the incident X-ray beam all round themselves, so that they may be compared to a point at the apex of a cone formed by the reflected rays, the result in the photographic plate will clearly be a ring which we can think of as the base of the cone.

As there are a large number of different atom planes in the crystal there will be many rings in the diffraction pattern. The powder method was subsequently modified by Professor Bragg for use with his ionisation spectrometer and this combination of two methods has been the means of producing results of the greatest importance.

CHAPTER X

APPLICATIONS OF X-RAY SPECTROSCOPY

PROFESSOR V. LAUE'S inspiration has already proved of the greatest practical value not only in the advancement of scientific knowledge, but also to general industry.

The credit for the manifold applications of the method is chiefly due to Professors W. H. and W. L. Bragg. The X-ray spectrometer which they devised will certainly become an indispensable instrument in many fields of investigation. It may, as we have said, be regarded as an ultra-microscope. Metallurgy and Chemistry have already benefited by its use, but in no way comparable to the extent that they will benefit by it in the future.

Let us in the first place consider how it has been of service to the chemist. It is only possible to quote one or two examples, but they will serve to indicate the immensity of the field which is awaiting investigation. It is convenient if we deal for a moment with some of the problems which concern the organic chemist. This being so one's first business is with the element carbon, which may be regarded as the nucleus of his whole activity.

Carbon is a very common yet a very curious substance, and it possesses very diverse properties which entirely depend upon the manner in which the carbon atoms are arranged with respect to each other. Graphite is carbon and nothing else, and so is the diamond. Graphite is very common and very cheap. It is very soft and consequently it is a very good lubricant. The diamond is comparatively

rare, it is very expensive. It is one of the hardest of all substances, and consequently it could never be used as a lubricant. These very opposite attributes of two slightly different arrangements of the same atom have been most beautifully explained and illustrated by Professor W. H. Bragg. He obtained crystals of graphite and crystals of diamond and subjected them to analysis by his X-ray spectrometer. He measured the dimensions of the planes

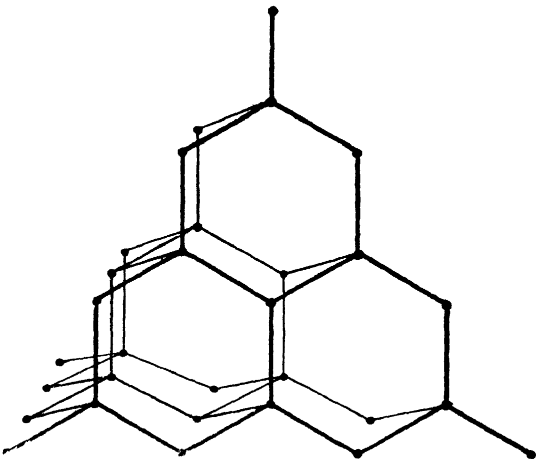
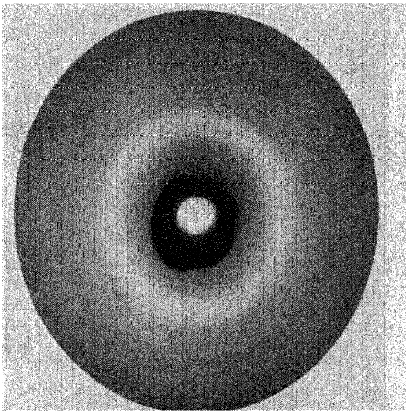
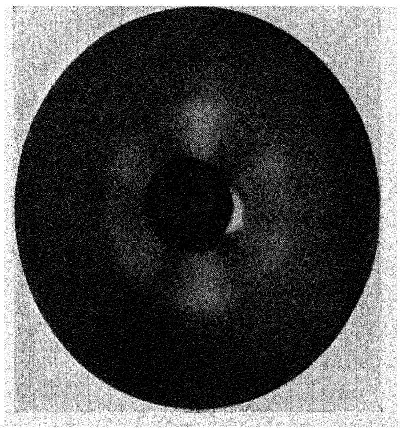


FIG. 11. DIAGRAM OF THE DIAMOND LATTICE

separating the atoms of carbon, and as a result he was able to construct ~~models showing~~ how the carbon atoms were arranged to make up the crystals of the one and the other. The diamond model which Bragg constructed is shown in Fig. 11. Each little dot is a carbon atom and they are arranged at equal distances one from another after the manner shown. They are packed evenly in what is known as a tetrahedral form. Each carbon atom exerts an equal attractive force on all its neighbours, and in this fact lies the secret of the hardness of the diamond. Fig. 12 shows the graphite crystal model. Here again each



Characteristic of a metal consisting of irregularly arranged small crystals



Characteristic of a metal in which the crystals have been caused to assume a more regular arrangement

FIG. 13. X-RAY SPECTROGRAMS

little dot is a carbon atom. The similarity in arrangement is very striking; but it will be noticed that whereas in the diamond the atoms are all equidistant, in graphite there is a much wider space separating each layer of carbon atoms. This wide spacing is, in fact, just a little more than double the distance of the corresponding plane of the diamond. The atoms which are separated by this plane have very much less attraction for each other in the graphite than the diamond. Their hold is infinitely more feeble, and so they are very easily plucked or even brushed apart. Thus it is that graphite is a good lubricant. Any shearing force

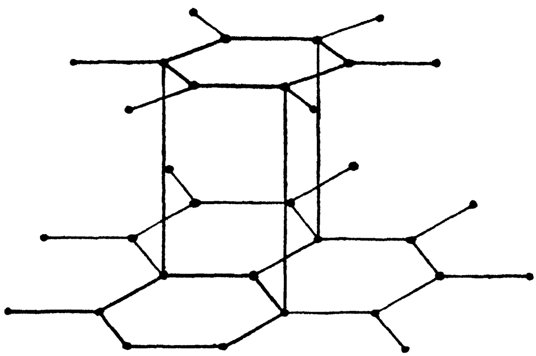


FIG. 12. DIAGRAM OF THE GRAPHITE LATTICE

applied to graphite rubs off layer after layer of carbon atoms separated by this plane. It is known as the cleavage plane of the crystal. It is the plane of maximum weakness. The corresponding plane in the diamond—that which is parallel to the table on which the model stands (Fig. 11)—is also a cleavage plane, and although nothing to be compared to the weakness of that of graphite, yet it is the weakest part and advantage is taken of its presence when it is desired to cut a diamond. Skilled workmen are able to split the diamond by reason of its possession of a cleavage plane. When we consider that the distance separat-

ing the carbon atoms in the diamond is in the neighbourhood of a hundred-millioneth of a centimetre it is amazing to realise that if we just a trifle more than double this distance between two layers of atoms we account for the vast differences in character between a diamond and a piece of graphite such as is found in an ordinary lead pencil.

The investigation of the structure of graphite by X-rays has proved of great service in investigations concerning the ability of charcoal to absorb gases. It is found that the particular modification of graphite structure is the determining factor in this important property, which gave charcoal such value in the Great War as used in the form of anti-gas masks.

For many years the organic chemist has been able to form some idea of the structure of molecules. He has known for example that the molecules of many substances are built up on a ring of six carbon atoms, known as the "benzine ring." This knowledge was deduced from considerations of valency. Other molecules, for example the paraffins, were built up on a *chain* of carbon atoms; and still other types of molecules by removing hydrogen atoms from such a chain and substituting other atoms or groups of atoms in their place. It was not, however, until X-rays were used to analyse the napthaline crystal that the reality of the "benzine ring" was proved. Crystals of substances belonging to the chain groups have also been examined by the X-ray spectrometer and the definite arrangement and dimensions of the molecules have been measured. Thus the X-ray spectrometer has enabled the organic chemist to construct definite models of his complicated molecules rather than represent them by diagrams of "C's" and "H's" connected by lines. In other words X-rays often permit of exact measurements in organic chemistry which take the place of uncertain although ingenious speculation. It is worthy of mention however that the ideas of the chemists concerning molecular struc-

ture have been proved to have had an almost uncanny accuracy.

If we take a certain number, say six, of these ubiquitous carbon atoms together with ten hydrogen atoms and five oxygen, and arrange them in a certain definite order we have a little unit which is the elementary form of a most important substance known as cellulose. It is the basis of a large number of fabrics including the now popular artificial silk and it is also the fundamental constituent of certain explosives.

The actual structure, size and shape of the cellulose molecule has for a long time been the object of intensive investigation. From its behaviour under different circumstances the chemist has been led to believe that it took a very large number of the little units to which we have referred to make up the molecule of cellulose. Cellulose is very definitely crystalline in character and therefore by examination with the X-ray spectrometer it was thought that the size of the molecule could be deduced by determining the size of the little crystal bricks. The result of this X-ray analysis so far seems to indicate that the cellulose molecule is not large as the chemists have imagined but rather that the crystalline character is conferred by the regular piling of the little units ($C_6H_{10}O_5$) or possibly $(C_6H_{10}O_5)_4$ as individuals. A further X-ray investigation suggests that whenever cellulose is interfered with by being made to combine with another chemical, the change is accompanied by a disentegration of this regular piling and a consequent disappearence of its crystalline form. In other words the crystals become too small to be recognised as such. It may be found possible to combine cellulose with other chemicals without destroying its crystal character, and if this proves to be practicable its consequences may have very far reaching practical applications. When we remember that many of the properties possessed by a substance are due to the manner in which

its tiny constituent units are arranged, rather than to its chemical composition, we may imagine that this new knowledge concerning cellulose may have a great influence in determining its future use. Better wearing material may be produced and explosives of greater power may be made.

Very many other organic substances have been analysed by Sir William Bragg by means of his wonderful spectrometer and information of extreme importance to the industrial chemist has been obtained. One more interesting example may be mentioned. Some work recently carried out by Professor E. A. Owen at the National Physical Laboratory was able to supply industry with particulars as to the manner in which a diamond should be ground in order to be an efficient pivot. From what was said in the beginning of this chapter it will be clear that a diamond is harder in some directions than in others. The X-ray examination of a number of diamond pivots, carried out by Professor Owen, showed in the most beautiful manner that the point of the pivot was frequently in the wrong place and so was liable to wear and consequent loss of adjustment of the pivot. The extreme minuteness of the specimens in this investigation rendered the technique a matter of great difficulty and added immeasurably to the interest and beauty of the results.

Metallurgy offers a very attractive field of work for the X-ray spectroscopist. The earliest important work in this application was carried out by Dr. Arne Westgren of Sweden. It was an extension of some work already done by Hull in America on the crystal analysis of iron. It was found that pure iron at ordinary temperatures has a crystal form that is called *centred cubic*. This modification of iron is called by the metallurgists *alpha iron*. It means that the little crystal units have an atom of iron at each corner and one in the centre. The eight atoms at the corners are of course shared with other adjoining crystal

units, and each crystal unit therefore contains two whole atoms. When, however, iron is heated to a high temperature, somewhere in the neighbourhood of 1000°C. its character changes. This form of iron is known to metallurgists as *gamma* iron. An X-ray spectroscopic analysis of this form shows that it has quite a different crystal structure. Each little crystal unit has an atom of iron at each corner as before, but instead of having another in the centre of the cube, it has *one in the centre of each face*. It is called a *face centred cube*. In gamma iron each little crystal unit contains four whole atoms. Iron in these two different forms has very different properties, and as a specimen may contain both modifications, its suitability for a particular purpose depends upon the amount of each form of iron present.

Each of these iron modifications is readily recognisable by means of the X-ray spectrometer and the relative amounts present in a specimen may be deduced with considerable accuracy—a result that is obtainable in no other way than by the use of X-rays. There are various other crystal modifications of iron and steel which have the most important bearing on its physical properties. By reason of the extreme smallness of the units responsible for these differences, X-rays alone can penetrate into this most fundamental mechanism.

If a metal is heated, its crystals grow in size and consequently the manner in which they reflect X-rays is changed. Further, if a specimen of metal, for example a sheet of copper, is passed through rollers, the rolling operation causes the crystals to assume a definite orientation. They tend to become preferentially arranged in the plane of the rolling. If a Hull X-ray spectrogram is obtained of such a specimen, it is observed that this preferential arrangement causes more reflection from some crystal planes than others, and is expressed on the photographic film as a number of blotches, or radiating spokes instead

of the characteristic concentric rings due to *irregularly* arranged small crystals.

A series of X-ray spectrograms is shown in the illustration. The first one shows the characteristic spectrogram of rolled copper, having small crystals preferentially arranged due to previous rolling, and so producing preferential X-ray reflection, characterised by a " spoke " effect in the spectrogram. The sheet was then annealed at the various temperatures shown, and it will be noticed that the X-ray spectrograms undergo a marked change. The first thing to notice as we progress up the temperature scale, is that as the crystals are thrown into violent agitation by the heat, they lose their regular arrangement, and the spoke effect in the X-ray spectrograms gradually disappears. The second striking thing is that as the crystals grow in size again owing to the higher temperature, the *regular* X-ray reflection as shown by circles or something approximating to circles, disappears and is replaced by irregularly scattered spots, which are characteristic of large crystals. These few remarks illustrate the way in which metals and their structure are investigated by X-ray spectroscopy, and it will be quite obvious that ability to acquire such intimate knowledge of what is happening *inside* a metal during or following any particular treatment, is of the greatest value. It must be noticed, that, unlike most methods of metallurgical investigation, X-rays may usually be employed without cutting up or destroying the specimen.

The significance of studying the inside of a metal is illustrated by X-ray investigation of strain. If a piece of metal is gripped at either end, and pulled, the atoms in each crystal tend to slip over each other, and to arrange themselves preferentially in the direction of the strain. If the strain is great enough, this atom arrangement communicates itself to the actual crystal boundaries, which also become elongated in the direction of the strain. When

it has reached such a point as this, strain is detectable by ordinary microscopic methods. If the surface of the specimen is polished, the crystal boundaries are easily visible. X-rays, however, may be used to detect strain *before* any modification of the crystal boundary occurs, because the X-ray reflection, which it will be remembered depends upon the arrangement of the atoms within the crystal, is altered by the slipping of the atoms within the crystal. The illustration shows such a strained test piece, together with X-ray spectrograms and the corresponding ordinary micro-photographs. In this particular case, the strain was increased until the test piece was actually broken. It will be noticed that preferential X-ray reflection indicating preferential atom arrangement, and consequently strain within the crystal, is visible long after the crystal boundaries show any distortion.

If we attempt to detect strain by reflecting X-rays from immediately below the surface of a strained metal, we may find that the result is negative, and that the atoms are unaffected. If, however, we use more penetrating X-rays, capable of being reflected from atoms a little deeper down, we get a positive result showing that although the strain is felt *inside* the specimen, yet it has not affected its immediate surface.

The wide use of electro-deposition of metals provides another very wide field for X-ray spectroscopy. Conditions of electro-deposition may be varied through very wide limits, and each set of conditions will produce a different sort of deposit exhibiting entirely different properties. Some deposits will be brittle, some will be tough, some will yield to a shearing force, and some will resist it. In other words, some metallic deposits will be suitable for one use, and entirely unsuitable for another. These varying properties depend very largely upon the manner in which the little crystals are piled upon each other. It is found by X-ray analysis that sometimes they are arranged

regularly and neatly like the bricks in a wall; on the other hand, under some conditions, they may be deposited in a chaotic manner. Further it may be that the crystals themselves are modified by the process of deposition when the properties of the metal again will be altered. The only way in which the properties of an electro deposited metal may be foretold with any real accuracy, is after crystal analysis by the X-ray spectrometer. It is not possible to recite all the problems of metallurgy which will benefit by the advent of X-rays, but nevertheless the reader will have formed some idea of the manner in which X-rays can be applied to certain problems when all other methods of investigation have reached the limit of their power.

In the very early days of X-ray spectroscopy, it was suggested that this branch of physics would prove of great value as a method of conducting chemical analysis. So far, this particular application is practically undeveloped, although some interesting results have been published by Dr. A. W. Hull, of America. The method he advocates is extremely simple, and depends upon the fact that no two similar substances have exactly the same molecular size, although they may have exactly similar crystal structure. The material to be analysed is powdered and placed in a glass tube. The X-ray beam is passed through it and the X-ray diffraction picture is registered on a film. Each chemical in the specimen will register its characteristic lines, and a measurement of these lines from a central spot on the film together with a determination of their relative intensities may be developed to afford a very accurate method of determining the constituents of the sample.

The fact that chemical analysis by X-rays has not been brought to perfection is not due to any inherent defect in the method, but rather to the simplicity and accuracy of prevailing methods of chemical analysis. It is very probable however, that industrial progress may ultimately

demand some such application of X-rays. When such a need arises, it is certain that it will be met by workers who will develop this property to a very high degree of efficiency.

There is another field for X-ray spectroscopy, as yet entirely unexplored. It would appear that as the different branches of science develop they tend to approach nearer and nearer to a common ground. This is very marked in the case of biological science. Atomic structure is responsible, as we have seen, for the various properties exhibited by inanimate objects, and it is possible that living organisms, if not life itself, may be explainable in terms of atomic or subatomic phenomena. It is certain that pathological tissue is a departure from the normal, not only in the coarse and visible way which hitherto has allowed its recognition but essentially in some more fundamental and vital manner. It has need of investigation and analysis in its minutest expressions. Although it is not claimed that the X-ray spectrometer is the ultimate refinement of analysis, yet it goes a long way beyond anything so far available. It should be applied to a study of disease and health. If physiological X-ray spectroscopy were developed as it certainly will be, that awe inspiring mite, the filter passing organism, should loom large as any elephant in our new vision.

CHAPTER XI

EARLY X-RAY APPARATUS

When we moderns, accustomed as we are to the elaboration and refinement of the X-ray equipment of the present day, look back at the results achieved by the X-ray pioneers of the year 1896, and see the simple and often crude apparatus with which they were accomplished, we cannot but marvel at the skill and patience of those early workers, and incidentally at the patience of their subjects, for exposures were necessarily protracted. In those days an X-ray set usually consisted of the two pieces of apparatus which are essential to the production of X-rays—a source of high voltage electricity to set the electrons in motion, and a vacuum tube in which the gas molecules have been so thinned down that the electron may have a chance to be accelerated to a really high velocity by the electric force before experiencing that sudden stoppage which is the birth of an X-ray.

It was with this simple apparatus, a small induction coil operating a simple vacuum tube, that Rontgen discovered his rays. The induction coil had been developing since Faraday's discovery of electro-magnetic induction. Essentially it consists of a coil of stout wire—the primary coil—surrounded by another coil consisting of a vastly greater number of turns of fine wire. This is the secondary coil. A steady current flowing through the primary coil sets up a steady magnetic field around it and has no result in the secondary, but when the current in the primary coil is

changing, as when it is first switche ond and is growing, or when it is switched off and is diminishing (both processes take an appreciable time), then the magnetic field is also changing. As we know, a moving magnetic field means a transfer of electro-magnetic energy, and the result is, as Faraday first showed, the generation of an electro-motive force in each of the turns of the secondary coil. In the induction coil the number of secondary turns is very large and the added effect of all the turns results in a very high voltage at the terminals of the secondary. The energy is not increased—we cannot take out more than we put in—so that the current is correspondingly small, but the voltage is so great that it will cause a spark to jump across a considerable air space. In practice the coils are wound on a soft iron core to increase the magnetic induction. The secondary has to be carefully insulated and is usually embedded in paraffin wax, although in recent years some makers have produced induction coils insulated by immersion in oil.

Although mammoth induction coils capable of giving electric sparks up to a foot or even two feet in length and representing voltages measured by hundreds of thousands had been constructed, these were unusual, but coils giving sparks of four or six inches length were common pieces of apparatus in the physical laboratories of the " nineties," and it was with this type of coil that most of the early X-ray work was done. The demand for X-ray apparatus at once gave an impetus to the development and improvement of the induction coil, and larger instruments soon came into general use.

We have seen that the secondary current is only induced when the primary current is changed. The more rapid the change the greater is the voltage produced in the secondary. The simplest way of producing such a changing current was to arrange some device which would continually interrupt the primary current many times a second.

The most usual type of interrupter was a simple piece of apparatus working on the familiar principle of the electric bell. A piece of iron mounted on a spring was attracted to the end of the iron core of the coil when the current was switched on. This movement broke the electric circuit, the magnetic attraction ceased and the spring pulled the iron back again, so re-making the circuit. This process being continuously repeated, produced a regularly interrupted current and worked fairly well for very small powers. When larger currents were used the sparking at the points where the circuit was interrupted very soon burnt the contacts away (although they were made of large pieces of platinum). Sparking at the contacts was reduced by placing a condenser across them, but still constant adjustment was necessary. The need for improvements in the interrupter was quickly realised and many types were experimented with, many of them developments of apparatus that had been tried and forgotten years before. The most satisfactory forms were those in which the circuit was made by dipping a piece of metal in and out of a vessel of mercury. An interrupter of this type devised by Sir James Mackenzie Davidson—the noted radiologist—came into very general use. A metal blade mounted on the end of the shaft of a small electric motor dipped into a pool of mercury, and so completed the circuit with each revolution of the motor. To prevent the mercury from oxidising too rapidly, it was covered with a layer of alcohol, but later this was dispensed with, and the containing vessel was filled with coal gas to displace the air—a method which is still used in all types of mercury interrupter.

This form of interrupter had a great vogue for some years, but as the demand for more and more power in the X-ray tube became incessant, it was dsplaced by the mercury jet interrupter, the form which is almost universally employed for operating induction coils at the present time.

In this the mercury is pumped up and forced through one or more fine jets, so striking against a series of rotating metal blades, or more frequently the jets are themselves rotated and the mercury impinges on a series of fixed metal blades. The circuit is completed each time a jet strikes a blade and in this way the circuit can be made, and what is more important, broken very rapidly and cleanly many times a second.

Still one other form of interrupter must be mentioned—the Wehnelt pattern. It is an electrolytic interrupter, the circuit being made between a lead plate and a small platinum point through the intermediary of acidulated water. Electrolysis of the water results as soon as the current is switched on, and a bubble of gas is at once formed around the platinum point and effectually breaks the circuit. The bubble disperses, the liquid flows back to the platinum, and the circuit is re-established and the process repeats itself. This happens many hundreds of times a second. The electrolytic type of interrupter had a very considerable vogue in America, but never found much favour in this country.

It will be realised that the induction coil gives us, not a continuous current through an X-ray tube, but a series of little bursts or impulses of high voltage current, and there will be one of these impulses every time the primary circuit is completed (or " made ") by the interrupter, and one each time it is broken. This brings us to one great disadvantage of the induction coil for X-ray work, for the induced voltage, and, consequently, the current driven through the tube on " make " is in the opposite direction to the current on " break." This is not what is wanted, for the current must always pass in the same direction through the tube—the target should always be the positive terminal and the other electrode should always be the kathode or negative terminal. If it were not so we should have electrons shooting *from* as well as *at* the target. Now, with

a well-designed interrupter, the break of the primary circuit is always very rapid and sudden, so that the secondary voltage produced by the break is far in excess of the " make " voltage. It is therefore the secondary voltage produced on breaking the primary that is used to operate the X-ray tube and every effort is made, by the design of the coil, and by methods that will be described immediately, to get rid of, or rather, to suppress as far as possible the voltage in the reverse direction, which is known as inverse voltage, and which would send an inverse current through the tube.

Inverse voltage is one of the bugbears of the X-ray worker. It causes the discharge of electrons from the anode, which, striking against the kathode or the walls of the tube, give rise to unwanted X-rays, so blurring the sharp definition of the shadow from the focal spot. It causes heating of the glass walls, it scatters, or " sputters," as it is termed, the anode metal, forming a black deposit on the walls of the tube, and so aids in the accumulation of stray electric charges which detract from the steady working of the tube and ultimately result in puncture of the glass by electric discharge.

The need for suppressing inverse current was quickly realised and very soon valve tubes were introduced. These are vacuum tubes, having a somewhat less good vacuum than an X-ray tube, which allow the current to pass very easily in one direction, but which offer a large resistance in the opposite direction. Their principle had been demonstrated by the work of Hittorf many years before. They are constructed with one electrode having a large surface in the centre of a bulb and the other having only a comparatively small surface confined in a small side arm. The large surface electrode can be readily bombarded by the gaseous ions in the tube and can produce a good supply of the current-carrying electrons. The tube will therefore allow the discharge to pass easily when this large

electrode is made negative, but in the reverse case, when the small electrode is the negative, a discharge can only pass with difficulty. This is the principle of the gas valve tube of which the designs have been many and which is still used on many small X-ray installations. Another device introduced some years later for the suppression of inverse discharge consisted of a mechanically rotated contact through which the high voltage current from the induction coil was led to the tube. It was mounted on the shaft of the interrupter motor (but of course insulated from it) and connected the tube to the induction coil only at the time when the interrupter was breaking the primary current and disconnected it during the time of making contact. This was a very satisfactory device for small powers and is still seen in use in many low powered sets.

The difficulty of inverse current would be avoided if it were a practical possibility to operate an X-ray tube from some source of constant high voltage current, such as is provided by a Wimshurst machine. A certain amount of experimental work in this direction was carried out in the early years. In this country the vagaries of electric machines in the constantly changing and usually damp climate put them out of court at once. In America, where conditions are somewhat more favourable, they met with a little more success, but even so the size and high speeds necessary for even moderate powers rendered them impracticable, which is unfortunate, for, from the X-ray point of view, they are ideal.

It was in tubes that the greatest variety and ingenuity was found in these early X-ray days. Very quickly it was discovered that an electric discharge passed through any form of vacuum tube in which the vacuum was good enough, would produce X-rays, and radiographs were obtained with such unpromising pieces of apparatus as a radiometer bulb and even an ordinary incandescent electric lamp! Rontgen made his discovery with a Crookes

tube—one of the pear-shaped tubes used to show the fluorescence of the glass walls. The kathodal electrons were shot over a large area and the sharpness of the shadows (or radiographs) produced was distinctly poor.

At first it was very generally thought that the fluorescence of the glass was necessary to the production of X-rays, but it was soon found that the point of impact of the kathode stream was the seat of the rays. In March, 1896, two months after the first news of Rontgen's discovery reached this country, Sir Herbert Jackson described the focus tube, in which the kathode stream was focussed by means of a concave kathode on to a small area of a metal target mounted in the centre of the bulb. This tube, except for the fact that the target was mounted at an angle of 45° to the axis of the kathode, was essentially the same as that designed by Crookes nearly twenty years before to show the focussing and heating effects of the kathode stream. In fact, several workers had been using this type of Crookes tube for the production of X-rays with excellent results.

By the end of the month the focus tube had come into general use and quickly supplanted all other forms. An immediate improvement in the quality of the radiographs produced was the result. Moreover, the vast increase in the output of rays and the tremendous gain in definition resulting from the focussing of the kathode stream made it possible to obtain far more detailed shadows on a fluorescent screen. Barium platinocyanide, the fluorescent substance which had first revealed the X-rays to Professor Rontgen, was the material with which these screens were usually coated, although potassium platinocyanide was sometimes employed. Energetic search was being carried out for a better material, a search which was not successful, for barium platinocyanide, in spite of its high cost, still remains the most efficient substance for the purpose. In this connection, an amusing telegram sent by

Edison to Lord Kelvin, in March, 1896, is worth quoting: "Just found calcium tungstate properly crystalised," he wired, "gives splendid fluorescence with Rontgen rays—far exceeding platinocyanide—rendering photographs unnecessary." This delightful piece of optimism was hardly justified, but the fluorescence of calcium tungstate has been of the greatest value in the preparation of what have become known as intensifying screens.

As early as the end of January, Campbell Swinton had suggested that the action of the rays on a photographic film might be intensified by placing a layer of fluorescent material against the film, or even by incorporating some such substance in the film itself, and, indeed, had experimented on these lines. By March a number of workers in different parts of the world had reported successful results, and calcium tungstate was found to be one of the most suitable substances for the purpose. Strangely enough, intensifying screens, although introduced so early in the history of X-rays, seem to have fallen out of use for many years. The reason for this appears to have been the difficulty of preparing fluorescing crystals of sufficiently small size. The comparatively large crystals, which gave the brightest fluorescence, gave a very granular picture, thus destroying the fine detail. It is interesting to note here that in the following year Dr. Max Levy used double-coated films having a layer of photographic emulsion on either side, which he placed between two intensifying screens. He reported that he was able to reduce his exposures from 12 to 15 times. This is a technique which has been reintroduced in recent years and which we are apt to regard as entirely modern!

Although the focus tube had immediately ousted all other types of X-ray tubes, a period of great experimental activity ensued with the object of developing and improving it. Campbell Swinton was an indefatigable worker in this field. At the Science Museum at South Kensington

there is to be seen a most interesting collection of his tubes, together with those of other experimenters. He examined the effect of altering the shape, size and disposition of the electrodes, and constructed tubes with electrodes, of which the position could be adjusted and thus give a certain amount of control over the " hardness " of the rays produced. Another interesting tube of this period preserved at South Kensington is a specimen of one of several metal X-ray tubes made in 1896 in Sir Oliver Lodge's laboratory. He had quickly realised the advantage that such a tube would possess and designed a metal tube with porcelain insulation. The difficulties were too great, however, and the provision of a practical metal tube is a need that has still not been adequately met.

From the earliest days of the study of the electric discharge through a vacuum tube it had been known that the residual gas is gradually used up, so that it becomes more and more difficult to get the discharge to pass at all —the tube becomes " harder." To overcome this trouble Sir Wm. Crookes had attached a small auxiliary bulb containing a little potash to one of his kathode ray tubes of 1879. By heating the potash it could be made to give off a little gas, which replaced the used up gas in the main tube, thus regenerating it. This is one of the first examples of a vacuum regulating device. Although the bulbs of X-ray tubes soon began to grow larger, so that the quantity of residual gas was greater, it was not long before almost every X-ray tube was provided with some regulator. An auxiliary bulb was attached containing potash, wax, or some such substance, which could be heated by a flame, or, more generally, by passing an electric discharge through two special electrodes sealed into the side bulb. A common form of regulator contained a rather thick piece of mica, a little air being driven out from between its layers when slightly heated. At a later date came the osmosis regulator, depending on the property of platinum

or palladium—particularly the latter—to allow hydrogen to pass through when made red hot. A small tube of one of these metals closed at its outer end was sealed into the wall of the vacuum tube. When heated by a flame, hydrogen from the flame passed into the tube. Another ingenious regulator was the Bauer valve—a sort of mercury trap by which a minute bubble of air could be made to enter the tube from the outer atmosphere.

In 1898 the self-regulating tube was introduced. Any of the discharge heated regulators were made automatic by attaching wires to the regulator terminals which could be brought near to the main terminals of the tube. When the tube began to harden it was easier for the discharge to jump across to the regulator terminals. This released a little gas, and the tube was thus softened, so that the discharge once more passed through the main tube instead of through the regulator.

During 1897 a third electrode had been introduced into X-ray tubes, originally by German manufacturers. It was placed at one side of the bulb and served as the anode, although it was generally connected outside the tube to the target which had hitherto functioned as anode. The latter electrode now became known as the antikathode—a name originally due to Prof. S. P. Thompson. The target in these tubes usually consisted of a thin layer of platinum rolled on to a nickel disc, for the need for a more substantial target than the pieces of platinum foil used at first had been quickly realised. Something had to be done to withstand and dissipate the large amount of heat produced by the electronic bombardment of the target. By the end of 1896 Campbell Swinton had made the first experiments in the direction of producing what became known as the heavy anode tube. He silver-soldered a piece of platinum foil to a penny and used it as the target. It certainly withstood the heating better and allowed him to pass a bigger current through his tube,

but the copper " sputtered " and became deposited on the glass walls. His next experiment was to press a piece of platinum into a small block of aluminium. This was successful, and thus was born the heavy anode tube.

As time went on targets became bigger and heavier. Later came the radiator tube, in which a metallic extension of the target was brought right outside the tube, the glass being sealed to a collar of platinum attached to it. Thus a great deal of the heat produced at the target was conducted outside the tube and there dissipated by means of radiating fins. Another method of keeping the target cool, which was quite early adopted, was to make it hollow, so that it could be filled with water. In some cases a water circulation was arranged, but there was a difficulty about this, in that the whole of the water circulating system was necessarily at the voltage of the target itself. The more usual arrangement, therefore, was to attach a small reservoir of water to the exterior of the tube. Both radiator and water-cooled tubes are in very general use to-day.

Platinum had originally been used for X-ray tube targets because it could be raised to a very high temperature without melting, but after a short time consideration began to be given to the question of the most efficient metal for the production of X-rays. S. P. Thompson pointed out that since the absorption of X-rays had been found to depend rather on atomic weight than on density, as was at first thought, metals of high atomic weight should therefore be the best emitters of X-rays. Sir Herbert Jackson had experimented with a great number of metals and Sir Wm. Crookes had, as early as June 1896, made a tube with a uranium antikathode, but had to abandon his experiments on account of the difficulty of obtaining the metal.

In 1898, Sir James Mackenzie Davidson introduced targets of osmium and iridium because of the great heat these metals could withstand. Tantalum was also used

for the same reason. Finally all these metals were swept aside by the all-conquering tungsten, the metallurgy of which had been developed by the electric lamp industry. Tungsten, with its high atomic weight and high melting point, as well as other special physical properties, has now become the standard metal for X-ray tube targets.

CHAPTER XII

EARLY APPLICATIONS OF X-RAYS

A SURVEY of the numerous and very diverse present day applications of X-rays cannot fail to impress us with a sense of the enormous practical value which has followed Rontgen's discovery. In the light of these modern applications, which even in this scientifically sophisticated age arouse genuine wonder, it is indeed remarkable that most of them were suggested, and in many instances actually used, during the first few months of 1896.

The first property of X-rays to be recognised was, of course, that by which they were discovered. They caused a certain salt—barium platinocyanide—to emit visible light. Furthermore, they had penetrated an opaque substance, black cardboard, in order to do so. It was this ability to pass through substances ordinarily quite opaque which caused the great scientific sensation. In his first paper Rontgen showed that he could obtain shadow images of metals when placed in wooden boxes and wrapped up in cloth. He also showed that while flesh was transparent to the rays that bone, like metal, was comparatively opaque. Rontgen had also noted that a very important property of his rays was their ability to affect a photographic plate exactly in the same manner as ordinary light. The first photographs of human hands showing the bones without the flesh appearing were described by a contemporary Viennese paper as being "ghastly enough in appearance." This description indeed applies to

all human radiographs, and its meaning becomes more intense nowadays as the increasing inquisitiveness of X-rays has laid bare our most intimate anatomical arrangements both physiological and pathological.

The practical value of the new discovery was of course immediately recognised, particularly in the domain of medicine and surgery. Rontgen was at once honoured by the German Emperor, and instructions were given by the German Minister of War that the subject should be investigated from the point of view of its possible service to military surgery.

It is very doubtful which aspect of the new phenomenon excited the greatest amount of interest—the question as to the nature of these mysterious rays or the more practical one : What could they do ?

From all over the world came reports of X-ray investigations. Perhaps the experiments carried out in England, by such investigators as Sir Herbert Jackson, Campbell Swinton, A. W. Porter and others, have the greatest interest. At the same time American workers were early in the field with very remarkable results.

Having discovered that certain substances, such as cardboard and wood, were penetrable by the rays, it was natural that many experiments were conducted to discover exactly which substances would allow the rays to pass and which would cast the best shadows. The substances so investigated were very diverse. It was soon found for example that water was transparent, and, again, that hydrogen, though a very much lighter gas than air, was not appreciably different from it in X-ray transparency. It was also shown at this time that a flame was transparent to X-rays.

Very shortly after these preliminary experiments, in fact, in January or February 1896, it was generally believed that the " density of a substance was the property whose variation mainly affects their permeability"

by X-rays. This determination, as we shall see later, was not strictly true. In April, 1896, however, it had been truly determined that the X-ray absorbing power of a chemical element depended upon its atomic weight.

Among the very early reports of medical and surgical applications there occur some items of particular interest. In a letter from America it was pointed out that X-rays had been used with conspicuous success in the McGill University, in Montreal; in fact, it was stated that Professor Cox had obtained a radiograph of a hand before any details from Germany had been received. It is of interest to quote from the letter to illustrate how very quickly this discovery in the realm of physics had been practically applied by the professors of a sister faculty. The method was tested on a patient with a bullet in the calf of his leg. The letter proceeds: "Forty minutes exposure produced a photograph showing very clearly the tibia and fibula within a veil of gauzy flesh and the flattened bullet lying between the two up against the inner angle of the tibia. Next day the bullet was extracted with an incision only two inches deep, whereas it was some *five inches from the entrance wound.*" It does not require much imagination to contrast this picture with that which might have been had the same result only been achievable after more extended surgical investigation!

Similar reports were constantly received. In January, 1896, the following applications had been very successfully tried. In Paris a diseased thigh bone had been diagnosed. In Vienna a bullet quickly located and removed from a hand. In Berlin the rays had been used to observe the formation of new bone following a fracture. The technique of the subject developed very quickly, and by the end of February 1896 the method was in comparatively general use; but although these very important results had been obtained and the future possibilities of the rays were so very hopeful there were many sceptical

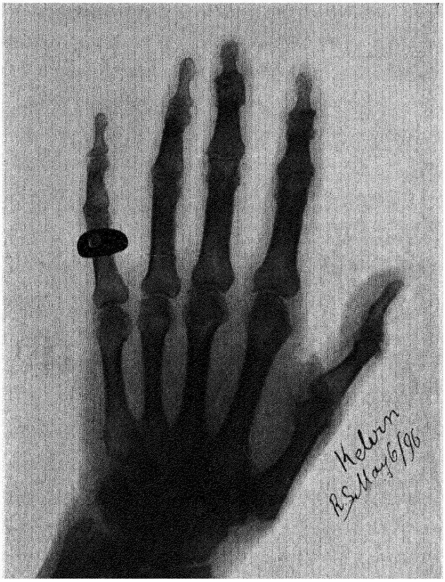


FIG. 16. RADIOGRAPH OF LORD KELVIN'S HAND
One of the first radiographs taken in England early in 1896 by Mr. A. A. Campbell Swinton, F.R.S. Note the transparency of the diamond in the ring

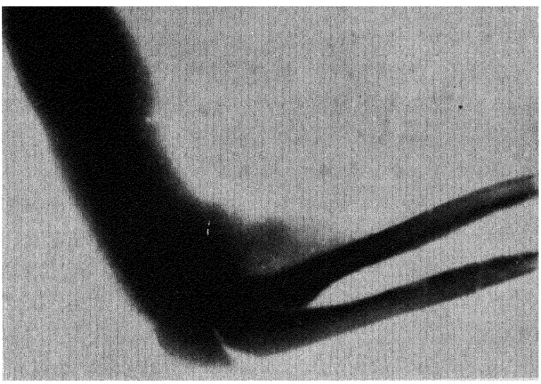


FIG. 17. RADIOGRAPH OF ARM TAKEN JANUARY, 1896, by J. E. PULLIN

critics. A very eminent surgeon of the time gave his opinion that X-rays would only be of value in a limited number of cases, and unless very considerable improvements were made in the technique it would be little resorted to in practical work. It will be observed that this opinion exhibits that caution which is so often a praiseworthy attribute of the man of science.

In May, 1896, the first periodical appeared dealing exclusively with X-ray matters. It was called the "Archives of Skiagraphy," and in this number was the most interesting statement that Dr. John Macintyre had exhibited at the Glasgow Philosophical Society an X-ray cinematograph film forty feet long, showing the movements of a frog's leg. X-ray cinematography is a subject which, although greatly to be desired, has not yet proved capable of satisfactory solution. During this year, too, the action of X-rays on micro-organism had been considered. These investigations will be referred to in a later chapter.

By the middle of 1897 the use of X-rays in medicine and surgery had become general and had proved to be an invaluable adjunct in diagnosis, and in some cases they had also been successfully used in treatment.

Early in 1897 a most remarkable radiograph was obtained by Dr. Morton, of New York. It was the radiograph of an entire adult body—a well-nourished woman fully clothed! The film was specially made for the purpose. The entire skeleton was successfully shown and the whole exposure including rest periods was only thirty minutes.

The following medical problems had now been attacked by X-rays: Localization of a bullet in the brain and a needle in the tonsil. Cavities in the lungs not previously suspected had been shown, and aortic aneurism had also been diagnosed or the diagnosis confirmed by an X-ray picture. Depilatory effects of X-rays had been demonstrated. Attempts had been made to treat cancer and

tuberculosis by X-rays and some improvements in cancer cases had been recorded.

When it becomes necessary to examine certain parts of the stomach and internal organs by X-rays it is the modern practice to administer to the patient a meal of some heavy salt, such as barium, which by reason of its high atomic weight is relatively opaque to the rays. When this meal is in process of digestion the condition of the internal organs through which it is passing is very clearly shown by means of radiographs. It is interesting to recall that this particular method of using the rays was practised before the middle of 1897. It was reported then that a fusiform dilatation of the œsophagus had been demonstrated by a radiograph after the patient had swallowed a cream of bismuth nitrate. Early in 1897 considerable attention had been paid to the accurate localization of foreign bodies. Stereoscopic methods had been tried and had yielded excellent results.

In Paris a framework had been constructed to carry two X-ray tubes, in order that a double picture might be obtained. The apparatus was used to localise a bullet in a living brain. The experiment was successful and the bullet subsequently extracted.

Early in 1898 Surgeon Major Beevor, in a lecture before the Royal United Services Institution on the use of X-rays in the Tirah campaign, recorded valuable results and emphasised the need for such equipment both at base hospitals and near the fighting line. X-rays had already been used by the German Red Cross Society in the Greek wars and by the United States army in Cuba.

It will be seen that the progress which has just been outlined was not inconsiderable, and it is so comprehensive as very generally to include nearly everything that is attempted at present. In the application of X-rays to non-medical matters the activity of X-ray pioneers was no less marked and in some respects the ingenuity dis-

played was even more striking. In addition to many really practical suggestions which, owing to the difficulty of technique and limitation of apparatus and power, had to be abandoned, there were some ingenious, although obviously less practical suggestions. For example, one enthusiast in America made the interesting suggestion in 1896 that X-rays should be used as a method of studying the bones in a bird's wing when in flight, it having been generally stated that the great drawback to aerial locomotion was our ignorance of the exact way in which a bird flies. Again, in 1899 "The Electrical Engineer" (New York) describes the Izambard process of printing by X-rays. A number of sheets of sensitised paper were to be piled up with the copy on the top and facing the X-ray tube. The copy was prepared with a metallic ink containing bronze or copper powder or alternatively white lead or white zinc. A pile of papers about two inches thick could be exposed at once without undue distortion of the shadow. This method was quite seriously considered, because some little time afterwards we find other writers suggesting modifications and improvements of the method. For certain obvious reasons, however, the matter could never have had any very satisfactory application.

Sir Richard Gregory tells of an amusing incident concerned with the very early days of X-rays. His experience appears to be the very first non-medical or industrial application of the rays. Very soon after the announcement of Rontgen's discovery, Professor Herbert Jackson was conducting some experiments with the new rays, to which he invited a few friends, Sir Richard Gregory among others. On his way to this meeting Sir Richard bought an umbrella. He was most careful to insist that the handle and the stick should be *all in one piece*. He was assured by the shopman that the umbrella he chose fulfilled the necessary condition. Sir Richard, however, was sceptical and con-

ceived the idea of testing his purchase by the new rays. Prof. Jackson applied the rays and it was clearly shown on the fluorescent screen that the umbrella handle was *screwed* into the main stick. We may imagine the consternation of the too sanguine shopman when the umbrella was returned. In view of the fact that X-rays are now so widely used both in this country and America as a method of examination of warlike stores, the following notice, which appeared in February 1896, has particular and prophetic interest: Professor A. W. Wright of Yale University " photographed a piece of metal having a fracture which had been welded, but showed no flaw or line of fracture to the eye. The photograph, however, revealed the fracture. This last result was considered by the Ordnance officials of the Government to be of profound significance, as indicating a means of testing armour for hidden defects and discovering hidden flaws in machinery."

Early in 1897 X-rays had been adopted in France by M. Pallain for the purpose of examining the interior of bombs, thereby foreshadowing another important use twenty-five years later.

We shall see that one of the most valuable future uses for X-rays will be in the examination of welded metal. The idea is by no means novel, for it was actually tried in 1896.

In the same year the French were using X-rays in the examination of coal for impurities. After many years this method is again being used with very successful results.

Professor S. P. Thompson referred to the work of Haycock and Neville with X-rays in 1897, in the investigation of the properties of alloys of gold and sodium, a study which had explained a long-standing mystery as to why the introduction of small quantities of a foreign metal reduces the electric conductivity of the alloy.

The detection of internal flaws in metals by X-rays was

successfully accomplished by M. Radiguet, in France, about the same time.

There were other applications almost too numerous to mention, but some of them may serve to give us ideas which may be more practicable now than then.

In San Francisco X-rays had been used in 1897 to detect adulteration of flour and sugar with sand or chalk. This important question of the detection of food adulteration was in fact very carefully considered in 1896 by Herr W. Arnold, in Germany, who applied X-rays with very considerable success. He measured the relative transparency of large numbers of food stuffs, vegetable oils and so on.

In 1901 M. Dubois records that X-rays may be used to locate pearls in pearl oysters without opening the shell or injuring the mollusc in any way. The process is said to be employed in the Ceylon pearl fishery, saving much time and preventing the unnecessary waste and thinning of the bed hitherto unavoidable.

Other applications, all in use in 1897, are as follows:

To distinguish between real and artificial gems—this is a most useful branch of modern X-ray application.

For the detection of the fraudulent introduction of mineral substances into textile fabrics to increase their weight.

To discover the contents of parcel post packages.

To recognise explosives and contraband in baggage.

To examine the insulation in electric cables.

In 1896 an amusing message from America was reported in "Nature." It was said that by coating the inside of a Crookes tube with fluorescent crystals Mr. Edison had produced an electric lamp in which "all the energy, which in incandescent lamps is lost in heat, is turned into light"—a high degree of efficiency which by no means characterises any X-ray phenomenon!

Very few of all these suggested X-ray applications were

proceeded with at the time. There were many factors involved in routine X-ray work which the early workers did not altogether appreciate. Electrical generators were unreliable and X-ray tubes were fragile and of very low power. Mortality among these tubes was very high indeed. Some of the physical aspects of the subject, such as scattering of the rays were not understood from the point of view of their significance in practical application. Many of the early suggestions which are eminently practical now had to be abandoned at the time owing to difficulties in technique. Results, however, were obtained, and when all the experimental difficulties of the time are considered the early achievements pay glowing tribute to the skill, perseverance and enthusiasm of the pioneer experimenters.

Another factor which mitigated against the more extensive use of X-rays in industry was the bugbear of X-ray disease, which made its unwelcome appearance at a very early date. It has claimed many martyrs, and it is only comparatively recently that suitable and adequate safeguards have been introduced.

CHAPTER XIII

MODERN X-RAY APPARATUS

DURING recent years a great change has come about in the radiologist's equipment. His heterogeneous collection of apparatus, frequently constructed for some quite different purpose and assembled together in a convenient corner, has given place to carefully designed and regulated outfits, adapted, with a multitude of accessories and refinements, for his own particular type of work. His apparatus is (or should be) designed to give adequate protection from the dangers of the X-rays themselves and from the risk of electric shock. It is arranged so that he may control at will both the quantity and the quality of the rays produced, and its power is vastly greater than was the case twenty (or even ten) years ago. Not only will it produce a far more intense beam of X-rays, but it can also, when required, give out rays of enormously increased penetrating power. It is this fact that has made possible during the last decade the extension of the usefulness of X-rays from purely medical work into the very valuable field of metal radiography.

Two important changes have combined to bring about this desirable state of progress. The induction coil, with its attendant interrupter, has given place (at any rate for all high power work) to the high tension transformer as the source of high voltage electricity, and the hot kathode tube has become available to replace the gas tube, which is the name now given to the type of X-ray tube the

development of which we have already described and which, it will be remembered, depended for its working on the fact that it contained a certain amount of rarefied gas to provide the current-carrying electrons.

The substitution of the transformer for the induction coil involves no new principle, for they are fundamentally the same—in fact, the induction coil is only a special form of transformer. Both have a primary and a secondary coil wound around an iron core, with the difference that in the transformer the two ends of the core are brought round and joined together, so that it forms a completely closed iron ring. With such a closed core the magnetising effect of the primary current is much greater—the magnetic field it produces is more intense. To operate such an arrangement by breaking the primary circuit by any sort of interrupter would be impracticable for the self induction of the circuit—that property, so akin to inertia, which tends to prevent any change in the quantity of electricity flowing in a circuit—would be too great. Self-induction would tend to keep the current flowing across the gap at each interruption, with the result that a great amount of sparking would be set up, which would immediately put the interrupter out of action.

This fact, however, is one that does not in the least distress us. The interrupter is at best a troublesome and uncertain piece of apparatus, and the fact that a transformer functions without any such accessory is perhaps its greatest advantage. The necessary movement of the magnetic field is produced in a transformer by supplying its primary with alternating current. Fortunately an alternating current supply main is now available in most places. Where continuous (or direct) current only is supplied it must be converted to alternating by means of a motor generator—a direct current motor which drives an alternating current generator (or alternator)—or by means of a rotary converter, which may be described as a com-

bination of the two units of the motor generator in one machine.

An alternator produces a voltage which rises to a maximum, dies away, rises to a maximum *in the reverse direction*, and dies away again, and it repeats this cycle continuously many times a second. Usually, in this country, it executes fifty complete cycles every second. The current which it sends through any circuit, therefore, alternates backwards and forwards fifty times every second and is *continually changing*. Flowing through the primary of a transformer, it produces a constantly changing magnetic field which induces a similarly changing voltage in each of the turns of the secondary winding. By making the number of secondary turns very large compared with the number in the primary, their cumulative effect produces a big secondary voltage.

As an example of what is involved in the construction of a high tension transformer we may take the case of one intended to work on a 250 volt supply main and designed to give a maximum secondary voltage of 200,000, which, high though it is, can only be regarded as a moderate figure for operating an X-ray tube for metal radiography. Such a transformer might have a primary winding consisting of say 100 turns and a secondary winding of about 60,000 turns, requiring a total length of some 35 miles of wire! The 400,000 volt transformer in the Research Department, Woolwich, believed to be the biggest X-ray transformer ever built, has no less than 86 miles of wire in its secondary winding!

Such extremely high voltages give rise to some difficult problems in the provision of proper electrical insulation. When it is realised that a voltage of 200,000 is capable of sparking across an open space of 14 inches and that a voltage of 300,000 will give a spark nearly 22 inches long, it is seen that the design of a modern X-ray transformer is no easy matter. For insulation between the different

layers of windings the splendid insulating properties of good quality paper are made use of, and a great deal of the supporting framework is also frequently constructed from an insulating material made of compressed paper. For general insulation the whole transformer is immersed in a tank of insulating oil. Not only has the possibility of sparking over or breakdown between different parts of the secondary winding to be guarded against, but also between the secondary and the primary or between the secondary and any parts of the apparatus, such as the outer case, which are connected to earth. Usually the centre of the secondary winding is connected by a wire to earth. The centre point is, therefore, at earth or zero potential and the two ends of the secondary are at voltages which are equally above and below earth potential—one end is positive, the other negative. In the case of, say, a 200,000 volt transformer, one end will rise to a maximum of 100,000 volts above zero, the other will be at 100,000 volts below, the total difference between the two ends being 200,000. In this way the tendency for any one part to discharge to earth is very much lessened, and the design of the transformer is facilitated and its bulk can be reduced. The insulation of the high tension conductors where they are brought out of the tank presents a difficult problem which has been variously dealt with by different designers. At Woolwich ebonite insulators have been found quite satisfactory for even the highest voltages by designing them so as to distribute effectually the enormous electrical stresses involved.

Although induction coils have been constructed to give extremely high voltages, they can never produce a large output of power—the current they can deliver at great voltages is always extremely minute. It is otherwise with the transformer. In the theoretically perfect transformer the secondary voltage is always a definite multiple of the voltage applied to its primary. If no current is being taken

out of the secondary, then the current that flows through the primary is very small. When the secondary voltage is allowed to drive a current through some connected circuit, then the primary current increases in proportion to the secondary current. The current which the transformer takes from the mains, therefore, increases or decreases with the current taken from the secondary—the secondary load. In practice there is usually a slight falling off of secondary voltage as the load increases, but this should not be serious in a well-designed transformer.

This ability to maintain a steady voltage is a most important point in favour of the transformer, which also scores over the coil in ease of control and general reliability, but both share the disadvantage of inverse voltage. In the case of the transformer we have seen that its output is constantly alternating—its inverse voltage is continually equal and opposite to the voltage in the useful direction—the direct voltage as it is termed. The very regularity and amount of the inverse voltage enables us to take advantage of this apparent drawback and to make use of the inverse current. We can so arrange the high tension circuit that the inverse current is not merely suppressed (as was the case with the induction coil) but can be actually made to pass through the tube in the same direction as the direct current, so that each half of the alternating current is in turn made to produce useful X-rays.

This conversion of an alternating into an undirectional current is known as rectification. The most usual method of effecting it is by means of a device known as a mechanical rectifier. It consists merely of a mechanically operated switch which is rotated by a synchronous motor —a motor so designed that its rotation keeps regularly in step with the alternation of the current. In the type generally employed each revolution corresponds to two complete cycles, which means that the direction of the current changes four times during each revolution. The rotating

switch is, therefore, arranged to reverse the connection wires from the transformer with every quarter revolution. so that the transformer terminals are alternately connected to opposite ends of the tube, and this change takes place regularly with the alternations of the current, which is therefore all passed through the tube in the same direction,

A mechanical rectifier is necessarily a rather cumbersome piece of apparatus, for the conducting parts must all be spaced out well beyond the distances over which it would be possible for a spark to jump from one to the other. A very frequent method of construction is to mount the rotating contacts on the edges of a large disc of insulating material which has to be two feet or more in diameter, according to the voltages involved. Since this large disc has usually to rotate at a speed of 1,500 revolutions per minute, it is necessary in the interests of safety to see that its construction is mechanically sound. The care necessitated in the maintenance of such a piece of high speed machinery and the noise produced by the whirling disc are perhaps the most serious objections to mechanical rectification, but since its introduction into X-ray practice in the Snook transformer in America in about the year 1908—which was the first practical application of the high tension transformer to X-ray work—it has become extremely popular. Where these objections are serious, rectification by means of hot kathode valve tubes of the type known as kenotrons is the alternative.

A kenotron is the modern counterpart of the gas valve tube, which has been described in a previous chapter. The principle involved, which is exactly the same as that of the hot kathode X-ray tube, will be dealt with a little later. For the moment it will suffice to say that it is a vacuum tube which will allow current to pass between its two electrodes in one direction only. A good kenotron will not permit any current to pass when a voltage of as much as 100,000 is applied to it in the *wrong* direction, and at

the same time offers very little resistance to the passage of the current in the right direction. It is clear, then, that by putting a kenotron in the circuit, or several in series—one for every 100,000 volts—if necessary, so that the current has to pass through them on its way to the X-ray tube, it will only be able to pass in the one direction. The direct voltage drives its current through the tube practically unhindered by the kenotrons, but the inverse voltage is opposed by an infinite resistance—the kenotrons interpose a gap which it is unable to bridge and no inverse current can pass.

This type of rectification, it will be noticed, makes use of the direct voltage only. It is possible by employing not less than four kenotrons to arrange a circuit so that each half of the alternating voltage is used. In the former case the discharge through the tube was in the form of intermittent pulsations, a short period of discharge being followed by an equal period during which nothing happened. In the latter method the pulsations follow one another without interval, and, under the same conditions, the current in the tube is doubled, for current is measured by the quantity of electricity passing per second. As we have seen, the current taken by the primary will also be almost doubled, but, in all probability, not quite, for a greater efficiency should be attained with this method of working. It is not met with very generally, however, for kenotrons are expensive, fragile, and of limited (although, with proper treatment, long) life. Moreover, they require expensive auxiliary apparatus, so that a slight gain in efficiency is probably more than counter-balanced.

There is another point that is often urged as greatly in favour of mechanical rectification. For each pulsation the voltage starts from zero, rises to a maximum and falls to nothing again. With kenotrons the whole of this changing voltage is applied to the tube, but, from the X-ray point of view, a considerable part of it is useless. The low voltage

will only set the electrons moving through the tube at comparatively slow speeds, and the X-rays they will generate will be too soft to have any practical value—the softest of them, indeed, will not even penetrate the glass walls of the tube. This would not matter if it were the whole story, but we have to remember that the X-rays produced account for only a very small fraction of the energy possessed by the moving electrons—the rest expends itself in heating the target. The slow moving electrons, then, produce no useful X-rays, but they add to the heat which has to be dissipated from the target and are therefore undesirable. With mechanical rectification we can, by shortening the rectifier contacts, arrange so that the tube is not connected to the transformer through the whole of a pulsation, but only during the high voltage part of it. Thus we have again a series of intermittent pulsations, the voltage varying during each, but never falling too low to be of value for the production of useful X-rays.

Looking at the subject from this point of view, it is apparent that the ideal method of operating an X-ray tube would be by means of a source of continuous (or direct, as it is usually termed), high voltage current, such as might be supplied by some super-Wimshurst machine or from a gigantic battery of some hundreds of thousands of primary cells or accumulators. Both are beyond the realms of practical possibility. It is only within recent years that the ingenuity of the electrical engineer has provided us with a method of obtaining a steady (or almost steady) high voltage discharge from the alternating transformer.

It is obvious that if we could, as it were, store up the electrical energy from our transformer in some reservoir on which the X-ray tube could draw, it would be possible to bridge the intervals between the successive pulsations. Fortunately, such a reservoir is ready to hand in the electrical condenser. Essentially, it consists of two metal

plates—usually sheets of tinfoil—separated by a thin layer of insulating material—the dielectric. If one of the two plates is kept at zero potential by connecting it to earth and the other is connected to, say, an electric machine, a quantity of electricity—depending on the size of the plates and the dielectric employed—flows into the condenser and is stored there. This convenient reservoir has then received a charge of electric energy which can be made use of just as it is required.

In order to put this idea into practice two condensers are employed, which are charged one after the other by a high tension transformer. Instead of the centre of the transformer secondary winding being connected to earth, the earth connection is at one end. Ordinarily, as has been explained, the bulk of the transformer would be increased by such an arrangement, but as this system has the effect of doubling the voltage applied to the tube, it need only be designed for half the maximum required. Suppose now the transformer is constructed to give a difference of 100,000 volts between its secondary terminals. The earthed end cannot change—it must remain at zero. The other end will alternately be brought to 100,000 volts above and 100,000 volts below earth potential—it will be alternately positive and negative with respect to the earthed end. By means of a rotating switch, similar to a mechanical rectifier, it is connected in turn to the two condensers, so that the one is charged positively to 100,000 volts and the other negatively. The anode end of the X-ray tube is connected to the former and the kathode end to the latter, the total difference of voltage between the ends of the tube being thus 200,000—twice that of the transformer. The energy stored up from each pulsation serves to supply the current for the tube until the next pulsation comes along ; the successful working of the scheme depends upon the condensers being large enough to supply the needs of the tube from one pulsation to the next. Instead of a mechanically

operated switch, two kenotrons may be used. One has its anode connected to the transformer terminal and so allows a positive charge to pass into one of the condensers. The other connects the transformer to the second condenser, but this one has its kathode connected to the transformer, with the result that its condenser can only be charged negatively.

Whether, when it has been fully developed and all its possibilities explored, direct current working will prove to be as advantageous for high power radiographic work as would appear at first sight, is difficult to say. The necessary condensers are large and expensive and must be particularly well made to stand up to the extremely high voltages. The most serious disadvantage seems to be a tendency to cause an early breakdown of the X-ray tube. Possibly the explanation will be found in the fact that the electric charges which are known to accumulate on the walls of a tube while it is running are able to reach a higher value under a continuous high voltage, so increasing the stress to which the glass is subjected.

It must be remarked that the apparent advantage of continuous high voltage is not nearly so great with a gas tube as with a hot kathode tube. Experiments with the oscillograph, an instrument that records the actual variations of current even though the variations occupy only a thousandth part of a second or less, show that the current through a gas tube is always varying, even when the voltage applied to it is continuous. The probable explanation of this is that the number of electrons produced by ionisation when the high voltage is applied to the tube is extremely large, so that momentarily the current through the tube reaches a very high value. This causes a drop in voltage and the ionisation decreases. The current falls, the voltage rises to its normal value again and the cycle repeats itself continually, each of these variations occupying but a minute fraction of a second. They are much too

rapid to be shown on any ordinary current measuring instrument, which merely records the average current passing. In the hot kathode tube ionisation plays no part in the supply of electrons, which are produced at a steady rate, depending on the temperature of the kathode, as will be explained later, and so the current through the tube remains steady.

We have now considered the various ways in which modern X-ray apparatus produces the necessary high voltage current. How, then, is it controlled and regulated? The actual amount of current taken from the transformer depends upon the X-ray tube. With the gas tube we were at the mercy of the condition of the tube—a factor that was ever changing. With the hot kathode tube the amount of current passing is under very exact control in a manner that will be explained a little later, and this fact constitutes not the least of the advantages of this modern type of tube, for it enables exposures to be repeated with exactitude.

The other factor that must be controlled is the voltage, and that depends upon the voltage applied to the primary winding of the transformer. In the early days of transformer working, as with the induction coil, the method was to cut the voltage down by interposing a variable resistance in the path of the primary current. Unfortunately for this simple arrangement, the same resistance "drops more volts," as the electrician expressively puts it, in proportion as the current increases, with the result that the secondary voltage of the transformer falls as the current taken from it increases. The modern method is to use, instead of a simple resistance, a piece of apparatus known as an auto-transformer. This may be briefly described as a low voltage transformer in which one winding is made to serve both as primary and secondary. By tapping off at various points along this winding the voltage supplied to the primary of the high tension transformer may

be varied at will, but once adjusted, will remain sensibly constant with varying loads.

In order to be able to repeat results, and for all experimental work, it is necessary to be able to measure accurately both the voltage applied to the tube and the current passing through it. A modern X-ray tube may be operated with a current of only a few milliamperes or it may momentarily be allowed to take 50 or 100 milliamperes. This current is almost invariably measured by passing it through a milliammeter of the type known as a moving coil instrument placed in the high tension circuit. The measurement of the voltages employed is unfortunately not so simple, for there is no entirely suitable practical instrument that will measure these high voltages. For a long time the only method in general use was to arrange a spark gap with sharp points between the two high tension leads to the tube. The points were brought closer together until the discharge started to spark across between them in preference to going through the tube. This distance, known as the alternative spark gap, does give an indication of the voltage, but is liable to much uncertainty. Far more accurate results are obtained by measuring the spark gap between two large spheres instead of between points, the gap being much smaller in this case, for spark discharges, and also the silent discharge known as corona or brush discharge, occur far more readily where the electric field is concentrated at a point. For this reason points and edges are carefully avoided in all high tension apparatus and the high tension circuits are connected by metal rods or tubes of half-an-inch or more in diameter instead of by wires.

A very usual way of indicating the voltage in a modern X-ray set is to wind a few turns of wire around the transformer core, separate and insulated from the other windings—a sort of second secondary in miniature. The voltage induced in these few turns is low enough to be measured by

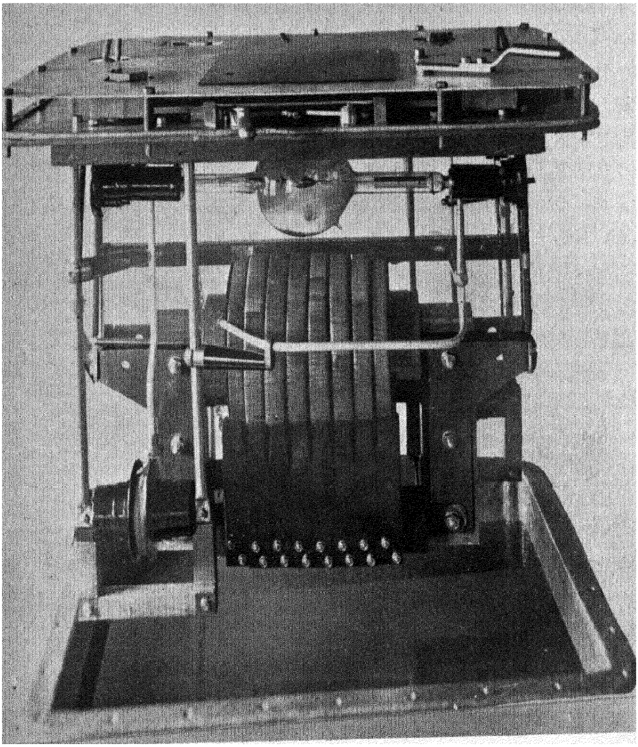


FIG. 19. SEMI-PORTABLE X-RAY APPARATUS CONSTRUCTED AT WOOLWICH FOR THE EXAMINATION OF AIRCRAFT PARTS AND MATERIALS

an ordinary voltmeter. The high tension voltage corresponding to various readings of this instrument is measured by the manufacturer by the aid of a sphere gap and, once calibrated in this way, the voltmeter readings serve to indicate the secondary voltage for future use.

Enough has now been said to give an idea of the main essentials of the different types of modern X-ray apparatus. No attempt will be made to give any account of the multiplicity of beautifully designed accessories which are available for the present day medical radiographer—couches with tubes in movable protective boxes both above and below, stands for screen examinations of patients, arrangements for stereoscopic radiography, and for the localisation of foreign bodies—all these and many others designed to render the X-ray examination or treatment of the human patient as safe, simple and efficient as possible. Those who are interested would gain much information from a perusal of the catalogues of the various manufacturers, and they would certainly conclude that the medical radiologist is well provided for.

Not so the industrial radiologist. As yet he is not so well catered for. Indeed, it is doubtful whether he ever can be, for his patients are so varied and their maladies so diverse that a general standardisation of apparatus (except in the fundamentals that have been described) would seem to be out of the question. Equipment that would enable the examination of, say, golf balls, or small pieces of electrical insulating material to be carried out expeditiously must necessarily be very different from that required for the handling of heavy engineering castings. A number of special X-ray sets arranged for the rapid examination of large numbers of different classes of articles have been designed at Woolwich, and the construction of special sets, each for their own particular class of work, and probably differing very widely from each other, is now becoming necessary with the advance of industrial

radiology. All industrial apparatus must be sturdily built, and to combine adaptability and strength with portability, so that subjects may be examined *in situ* (as for example welding in ship construction) is one of the greatest problems confronting the designer of modern X-ray apparatus.

CHAPTER XIV

MODERN X-RAY TUBES

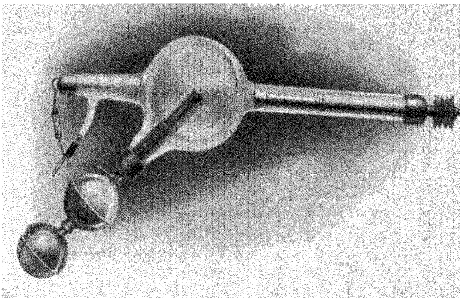
WE must now turn to that revolutionary change which, apart from its value to the medical radiologist has proved of first class importance in that it has made possible the practical application of radiology to industry—the introduction of the hot kathode tube. The essential feature of this tube is that it does not depend upon the ionisation of any residual gas to allow a current to pass. Its vacuum is made as perfect as possible and the necessary current carrying electrons are provided by using a white hot tungsten wire as the kathode. That free electrons are emitted from the surface of metals at white heat had been known for many years. The result of the study of this phenomenon—known as thermionics—by a great number of physicists, and particularly by Fleming and by O. W. Richardson, has had, perhaps, the most far-reaching results of any scientific work of recent years, for in addition to opening up an entirely new field of X-ray work, it has given to the world that modern worker of miracles—the " wireless " valve.

At the same time it must not be supposed that the gas tube has disappeared. It is still largely employed for medical work, but, except for the so-called " boiling water tube," has changed little during recent years. The " boiling water tube " is a large gas tube introduced in Germany to produce the penetrating X-rays now demanded for medical treatment purposes. Both its kathode and anode

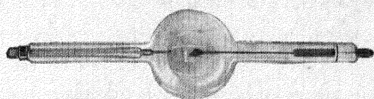
are water cooled, and the water in the latter boils during operation. To maintain the correct degree of vacuum an osmosis regulator is provided. When the tube hardens and the current through it falls, a contact on the milliammeter operates an electric relay circuit which turns on a gas flame arranged to heat the regulator, and so soften the tube. The tube will thus give a steady output of rays of one quality for long periods without attention. For its own particular purpose it is excellent, but it can never compete with the adaptability of the hot kathode tube for general work.

It was in 1913 that hot kathode X-ray tubes were introduced by Lilienfeldt in Germany and by Coolidge in America. In both, a tungsten wire, exactly similar to an incandescent electric lamp filament, heated by the current from an accumulator was used as the only source of electrons. Lilienfeldt placed his hot filament in an auxiliary bulb and by means of a comparatively low voltage of 2,000 or so propelled the electrons through a hole in the kathode where they were subjected to the full working voltage and so shot against the target. The arrangement was complicated in working and, in this country at any rate, the tube is of historic interest only.

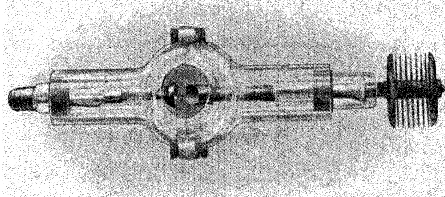
The Coolidge tube, like the original focus tube, has two electrodes only. The anode is a massive piece of tungsten supported on a molybdenum rod, and the kathode consists of a small flat spiral of tungsten wire set in a molybdenum hood. Wires from the ends of the spiral filament are brought out at the end of the tube and, by connecting these to a 12-volt battery, the spiral is rendered incandescent. Under the usual conditions of operating the tube all the electrons given off from the hot filament are immediately shot across by the electric force from the kathode to the anode. The number carried across, that is to say, the current passing through the tube, must therefore depend upon the number produced, and this increases



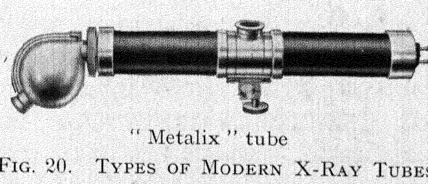
Boiling water tube—A modern gas tube



200,000 volt Coolidge tube



Coolidge radiator tube with lead glass shield



" Metalix " tube

FIG. 20. TYPES OF MODERN X-RAY TUBES

with the temperature of the filament. A very accurate and sensitive control of the current through the tube is obtained, therefore, by regulating the heating current from the filament battery. Actually a battery is rarely used for this purpose nowadays, for the whole of the battery circuit is connected, through the kathode, to one end of the high tension transformer and must, therefore, be insulated from its surroundings, and can only be controlled from a distance by an insulating handle. Usually a small " step-down " transformer is used—that is to say, one which takes the current from the mains and transforms it down to 12 volts in the secondary. The secondary winding is carefully insulated from the primary and from earth, so that the primary can be regulated by ordinary means. A slight alteration of the primary circuit changes the secondary current and thus regulates the kathode temperature.

It has been mentioned that a small hood surrounds the filament in the Coolidge kathode. Molybdenum is the metal used for this and for the anode support, because it can be raised to a high temperature without melting or undergoing any change, but is more easily worked than tungsten, which is used for the target because of its extremely high melting point and its greater density. The function of the hood is to focus the stream of electrons on to one spot of the target. When we want to obtain fine detail in a radiograph a very small focal spot is, of course, desirable. This limits the amount of power that can be put through the tube, for if the energy is all concentrated on a very small area the local heating becomes so intense that even tungsten, with its very high melting point, is fused. Tubes are, therefore, made with focal spots of different sizes, depending upon the position of the filament inside the hood, according to the purpose for which they are required. For medical treatment purposes a fine focus is of no importance, so that a broad focus tube allowing a

greater X-ray output is chosen. A method of increasing the possible power without losing the advantage of a fine focus is to use a line kathode, as in the German "Muller" tube. The filament is in the form of a straight spiral which gives a straight line focus. The X-rays given off along the *length* of this line proceed as from a small spot of the width of the line only, but with an increased intensity due to its length.

Most of the electrons from a Coolidge kathode reach the focal spot, but a number stray from the proper path and strike other parts of the anode, giving rise to a certain quantity of X-rays over a considerable area. Some electrons even reach and bombard the glass, a source of considerable trouble in the construction of extra high voltage tubes, often resulting in puncture of the walls and consequent ruin of the tube. A kathode has been produced in the Research Department at Woolwich in which the kathode hood is dispensed with and which largely reduces the number of these stray electrons.

Those who have seen a tube of the standard Coolidge type in operation know that the tungsten anode rapidly becomes raised to an intense white heat. There is now on the market a water-cooled Coolidge tube for very high powers. The target is cooled by a continual flow of water, but the whole of the cooling system must be insulated unless a transformer which is earthed at one end is available. There is also a radiator type for comparatively small powers, in which the target is cooled by an external radiator exactly as in the radiator gas tube described in a previous chapter. The radiator hot kathode tube, so long as its anode is really kept cool, has the advantage of being self-rectifying, that is to say, it will only allow a current to pass in the correct direction.

The reason for this is easy to see, for a current can only pass by the transfer of electrons from one electrode to the other. For a current to pass in the *wrong* direction, there

would have to be electrons travelling from the anode to the kathode, but so long as the anode is reasonably cold it can produce no electrons, and none can be provided by ionisation as in a gas tube, since the gas has been pumped out to such a degree that any ionisation is negligible. This is the principle of the kenotron. The electrons from a hot kathode travel across to an anode of large surface, and the kathode is always arranged to provide a large excess of electrons so that the effective resistance of the tube is small. The kenotron filament is heated from a separate battery or transformer, as in the case of the X-ray tube. The rectifying action of the radiator type of tube is extremely useful where only low power is required, in that it simplifies the apparatus, allowing the rectifier to be dispensed with.

Another type of Coolidge radiator tube is made with thick walls of lead glass with a small window of soda glass fused into it just in front of the target. The soda glass allows the rays to escape,but the lead glass absorbs a large proportion of the radiation which tries to pass through it. There is thus a localised beam of X-rays which can be directed where required, whilst the surrounding space is kept comparatively free from unwanted radiation, and the amount of external protection can therefore be much reduced. As an example of compact design, mention must be made of a small tube of the radiator type, which is mounted inside the case of a small high tension transformer and immersed in the transformer insulating oil. The bulk is thus reduced to a minimum and, moreover, no dangerous high tension wires are exposed. A special window through which the rays will pass easily is provided in the transformer case. This apparatus is designed for dental and medical radiography where portability is of first importance.

A novel departure from the conventional design of X-ray tube has been made in recent years by the Philips

" Metalix " tube. A hot kathode and a tungsten target are used, but a considerable portion of the tube wall is made of metal. An alloy of iron and chromium is employed. Usually, when metal has to be sealed to glass, platinum has to be used as an intermediary, because it is the only metal which expands on heating by approximately the same amount as glass. By choosing the correct proportion of the two metals in this alloy its expansion can be made equal to that of the glass, which can then be sealed directly on to it without the use of platinum. The usual bulb form of X-ray tube is dispensed with in the Philips tube, which is cylindrical in shape, having very much the appearance of a large electric torch. Glass is used where it is necessary for the insulation of the high tension leads and for a window to allow a beam of rays to escape. The metal walls, reinforced by an outer layer of lead where necessary, serve to check the output of X-rays in other directions, and it is claimed that no additional protection is required. For ordinary work of low power the convenience and portability of this tube should prove extremely useful.

This approach to an all-metal X-ray tube is perhaps an indication of one of the lines of future development. The term " all-metal " is, of course, a misnomer, for no tube can be constructed entirely of metal. The electrodes must be insulated, and this necessitates the use of some such insulating material as glass, silica or porcelain, for it must be vacuum proof and able to withstand high temperatures. For high voltages this insulation must necessarily be of considerable extent, so that for really high voltages a very large proportion of the tube would always have to be of glass or some non-metallic material. For X-ray spectroscopy, where a steady output of low voltage radiation is required for long periods, metal tubes have been constructed by Shearer, Siegbahn, Coolidge and others, but these have to be kept continually attached to a vacuum

pump, on account of the perpetual evolution of gas from the metal when heated by the discharge. One of the greatest difficulties in the construction of a metal tube is to produce metal free from minute flaws or porosity which would gradually allow air to enter, and so spoil the necessary vacuum.

For gas tubes large bulbs of seven or eight inches diameter are employed in order that the tube may not harden too rapidly. For hot kathode tubes of high power, in which the target is rapidly raised to a high temperature during working, the bulbs have to be of a similar size for a different reason. The large diameter is necessary, as otherwise the glass might be softened by the heat from the target. By the use of silica (fused quartz) instead of glass, tubes of much smaller size can be made, because of the heat resisting properties of silica. The construction is difficult, but it is probable that more use will be made of this material in the future.

The most urgent need for the advancement of radiography is the development of X-ray tubes to operate at extremely high voltages. Until comparatively recently 200,000-volt tubes were the most powerful commercially obtainable, but there is now on the market a large Coolidge tube rated at 250,000 volts. This tube has a glass bulb eight inches in diameter and an overall length of some three feet. For higher voltages still longer tubes are required. The exhaustion must be very thorough, and this entails not merely pumping the air out of the tube by means of a high vacuum pump and then sealing it off, but baking the tube at a high temperature and then passing a heavy electric discharge through it for many days, pumping all the time to remove the air and other gases which adhere with great persistence to the glass and the metal electrodes. Although tubes for higher voltages can be made, their construction is extremely difficult and prolonged and their life, at present, all too short. At these tremendous

voltages the glass is subjected to very great electrical stresses. Stray electrons bombard the glass and unwanted electric charges accumulate in unexpected places, with the result that the glass breaks down and a puncture results. The causes of breakdown are many and varied, and it must be admitted, even after much research, not all of them are properly understood. Nevertheless, much progress has been made and there is every probability that ultimately reliable X-ray tubes operating at far higher voltages than those of the present day will be produced.

CHAPTER XVI

X-RAYS IN PRACTICE

When we begin to consider the means by which X-rays may be turned to practical account we find at once that there is one important limitation when they are compared with visible light. There is no lens that will refract X-rays and bring them to a focus, and we are therefore limited to the production of shadow pictures. We can only place any object we wish to examine in the path of a beam of X-rays and observe, by some suitable means, the shadow it casts. The shadow will be only a partial shadow, because some of the rays will have passed right through it, but their intensity will have been reduced by an amount depending on its thickness and the material of which it is composed, and also, of course, on the penetrating power of the rays employed.

The power of a substance to cut down the intensity of an X-ray beam, that is to say, its opacity to the rays, was at first thought to depend upon its density, but it was soon found that the real factor concerned was the weight and number of the atoms through which the rays had to pass. In general, the greater the atomic weight the more the rays are stopped by an atom, so that lead obstructs the passage of the rays more than iron, iron more than aluminium, aluminium more than organic substances, such as wood or flesh, which are compounds of carbon with other light atoms. Whether the atoms are free or in chemical combination with other atoms does not matter—each

individual atom will still do its share in obstructing the rays. Thus, bone, which contains a certain proportion of lime (calcium) salts, is more opaque than flesh. Increasing the thickness of a layer of a substance through which the rays have to pass merely means that there are more atoms to obstruct the rays, so that less rays emerge on the other side.

Penetrating power is a matter of the wave length of the X-rays, and in general the shorter the wave length the greater the penetration, but it must be remembered that any substance is abnormally absorbent to rays of just the right wave length to produce its characteristic radiation. Speaking generally, however, we may say that the higher the voltage applied to the X-ray tube the more penetrating will be the X-rays produced.

It is clear, then, that if a beam of X-rays of suitable penetrating power passes through an object of varying thickness or varying composition, the emerging rays will have different intensities, corresponding to the variations in the object. Whether the variation is apparent on the surface of the object or not, the effect is the same. A hidden cavity in a metal casting merely means that the total thickness of metal is reduced and the intensity of the rays that have passed through that part of the casting is cut down less than by the solid metal. We cannot see the rays. How, then, can we compare the varying intensities that are emerging from the object ?

A number of possible methods present themselves, but there are only two in general practical use. The simplest and most direct is to place a fluorescent screen in the path of the emerging rays. The X-ray energy, or rather a proportion of it, is absorbed by the crystals of which the screen is composed and causes them to fluoresce, which really means that the energy absorbed in the form of X-rays is transformed and given out again in the form of the much longer waves of visible light. The brilliancy of

the fluorescence depends upon the intensity of the X-rays, so that where the object is most transparent the screen is most brightly illuminated. The great limitation to the use of the fluorescent screen lies in the fact that a fairly large X-ray intensity is needed to produce any visible fluorescence at all. It is therefore useless for the thicker and more opaque specimens, which allow only a trifling amount of even the most intense beam of rays to emerge. Two types of fluorescent screen are in general use—the barium platinocyanide, giving a greenish fluorescence, and the " white salt " screen, coated with crystals of calcium tungstate, which fluoresces blue. For the comparatively long wave radiation used in medical work the former seems superior, whilst for the very penetrating rays used for the examination of metals the latter appears slightly more efficient.

The second, and by far the most generally used practical method of examining the rays which have passed through a specimen is to make use of their photographic effect. Their action on a photographic emulsion is exactly similar to that of ordinary light, so that if a photographic plate is placed where the rays fall on it, it is found, after development by the ordinary photographic process, to be most blackened where the object was most transparent and less blackened where it was more opaque. Thus we have recorded a photographic negative of the transparency of the object; in other words, a radiograph. From this negative positive prints can be produced if required by the ordinary photographic printing processes. During exposure the plate must, of course, be protected from ordinary light, so that it is usually wrapped in black paper, which may be regarded as being completely transparent to the X-rays ordinarily employed.

The greatest advantage which the photographic method has over all others is the cumulative action of continual exposure. The effect on the emulsion depends upon the

intensity of the radiation and the time for which it acts, so that by exposing for a sufficient time the feeblest amount of radiation may be recorded. The quantity of rays which succeed in getting through the object must, of course, depend upon the intensity of the original beam of rays coming from the tube; that is to say, on the current passing through the tube. The exposure of a radiograph is therefore usually given as the product of this current and the time, and is expressed in milliampere-seconds or milliampere-minutes. The radiation reaching the plate will also depend upon its distance from the target of the tube, since the intensity of the radiation diminishes as the square of the distance it has travelled, so that to be able to repeat an exposure we must know this and also the penetrating power of the rays employed, which in practice is usually denoted by the voltage applied to the tube, generally expressed in kilovolts (one kilovolt is 1000 volts). A typical statement of the exposure of a radiograph would therefore be 5 milliampere-minutes at 200 K.V. (kilovolts) 18 inches distance, which would be a usual exposure for an inch of steel *without* intensifying screens. To specify completely the conditions we must also know the type of X-ray tube employed and the type of electrical apparatus. The X-ray output from a tungsten target tube will not necessarily be the same as from a tube having a platinum target, nor will a gas tube give quite the same result as a hot kathode tube, even with the same voltage and current recorded. Again, the effect with a transformer will differ from that with an induction coil.

Unfortunately a photographic emulsion catches and makes use of only a very small proportion of the X-ray energy that falls on it, much less than one per cent. The rest passes right through and is wasted, although special emulsions containing as many heavy atoms as possible are used. Modern technique, therefore, makes use of films coated with sensitive emulsion on both sides, the second

coating catching some of the rays which have passed through the first. This in itself represents a distinct gain in efficiency, but its full value is realised when the action of the rays is aided by the use of intensifying screens, as two of these screens can be employed—one on either side—thus increasing the photographic effect some thirty to forty times. It will be remembered that intensifying screens and even double coated films were introduced in the very early days of X-rays. A modern screen is a vastly improved affair, and in good specimens the objectionable grain caused by the size of the fluorescing crystals has been completely eliminated. It is very necessary for the intensifying screens and the film to be in as close contact as possible, and they are therefore compressed together in a light-proof casette during exposure.

Another method which might be used to compare the intensities of the emerging X-rays would be to examine their ionising power. This method is extremely useful in the physical laboratory and is in very general use for the comparison of intensities in X-ray spectroscopy. If we could take a small ionisation chamber and pass it across, say, a piece of metal which we are examining for internal flaws, any variation of the intensity of the rays coming through the metal would be indicated by a change in the ionisation current. This at first sight appears to be an ideal method of making rapid practical X-ray examinations at any rate, in certain cases, but the practical difficulties are many. The current produced in an ionisaation chamber is always so minute, even under the most favourable conditions, that to measure it requires sensitive apparatus which can only be used in the laboratory. If we could produce an ionisation current of such magnitude that its strength could be indicated by the movement of a pointer over the dial of some sturdy portable instrument the method might have exceedingly valuable applications. It is possible that something of the sort may ultimately be

achieved by valve amplification of the feeble ionisation currents in the manner in which the minute currents concerned in wireless telephony are amplified, although so far practical results have not been arrived at.

Still another method which may some day be developed would be to pass a small selenium cell across the specimen under examination. Like ordinary light, X-rays cause a change in the electrical resistance of this peculiar element, and so produce a change in the value of a current flowing through it. Selenium can be prepared so that a comfortably measurable current can be used and so that it is sensitive to X-rays of only moderate intensity. The great trouble, however, is that it only recovers very slowly from any change of resistance and also that it seems to be subject to spontaneous changes from time to time, so that its indications are very unreliable. In Germany Furstenau claims to have prepared selenium cells more or less free from these defects, and uses them for the measurement of X-ray intensity in medical treatment, where they are operating under fairly steady conditions.

There are, then, two generally used practical methods of radiological examination—by means of the fluorescent screen or by taking a radiograph, the latter being far the more sensitive and permitting the examination of much thicker specimens. If the rays were merely absorbed in varying degree by the substances through which they pass, radiography would be a comparatively easy matter. We know, however, that a very large proportion of the rays are not absorbed at all, but are scattered in all directions by any material which they encounter. Even the molecules of air through which the rays pass scatter some of them, and with the high power radiation used for metal radiography the scatter from this source alone is very considerable. In fact, the amount of this general scatter from the air and from surrounding objects which occurs in high power work is surprising and frequently underrated.

It must be remembered that the scattered rays can themselves be scattered again and again, with the result that the whole of the atmosphere even at a considerable distance from a powerful X-ray tube is filled with rays travelling in all directions.

If any of these scattered rays reach the screen or the photographic film they will cause a general fogging which, if the exposure is at all prolonged, may obliterate all the detail required. The first practical point, then, is to suppress all the rays coming from the tube except those which are actually falling on the specimen, a precaution which is, of course, necessary for the protection of the operator as well as to ensure a satisfactory radiograph. Generally this is accomplished by enclosing the tube in a lead box (or a box made of some material containing a large amount of lead, such as lead-rubber) having an adjustable aperture the size of which can be controlled by lead diaphragms. Here it may be worth remarking that the commonly-made statement that X-rays cannot penetrate lead is completely untrue. It is quite possible to take a radiograph through a sheet of thin lead. Because of its high atomic weight lead is comparatively opaque to X-rays and, if of sufficient thickness, only allows an immeasurable and entirely negligible quantity of radiation to pass. For radiography at 200 K.V. and over, the thickness of the tube box should never be less than a quarter of an inch of solid lead.

Even with this limitation of the direct beam there will be a certain amount of general scattering both from the air, the object itself, and also scattering of the rays which have passed right through the object and the film. The film, or rather the casette in which the film is held, must therefore be surrounded by lead, except on the face just where the useful direct rays reach it, as shown in Fig. 21. When the whole of a small object has to be radiographed care must be taken that no part of the direct beam of rays

from the tube is allowed to pass by its edges, and with objects of irregular contour this frequently calls for much ingenuity. Often much can be done by carefully cutting lead sheets to fit around the specimen. Sometimes powdered lead packed around it, holes being first filled with

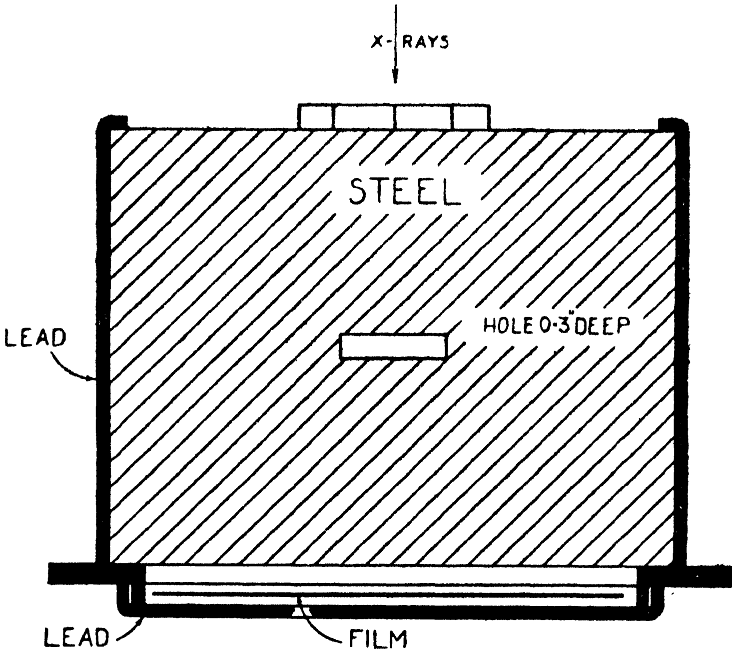


FIG. 21. DIAGRAM SHOWING SECTION OF 4½IN. BLOCK OF STEEL ARRANGED FOR RADIOGRAPHING

wax, provides an easier method. Again, in some cases soft wax loaded with red lead may be moulded to the sides, or it may even be necessary on occasion to cast lead or type metal around a specimen. Each and every case presents a different problem, which must be dealt with as circumstances permit, but, whatever is done, this screening must be perfect. Even a tiny hole, if it allowed the intense direct beam from the tube to reach the film,

would cause extensive fogging and, more important still, might give rise to patches of slight fogging in unexpected places, which would possibly be taken as evidence of defects in the specimen and so give entirely false results. Fortunately, in the majority of cases it is only necessary to radiograph a portion of an object and this difficulty of edges is avoided.

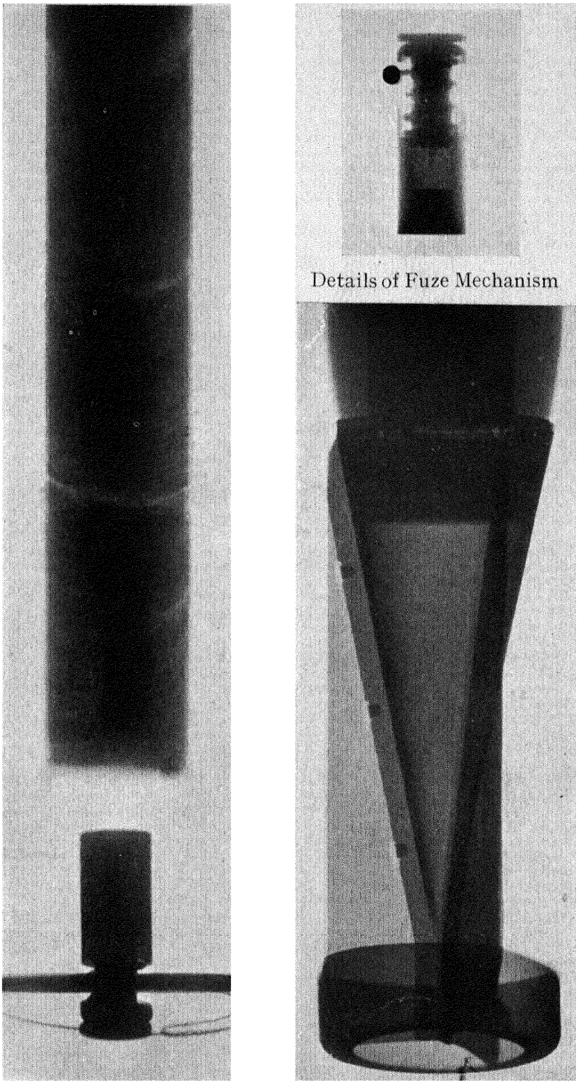
When we want to obtain fine definition in our radiograph we employ a tube having a small focal spot and also reduce the relative size of the spot by removing the tube as far from the object as is practicable. The limitation to this is the increase of exposure involved. The screen or film must be as close to the specimen as is possible. We have to remember all the time that we are dealing with a shadowgraph, and the conditions must be similar to those under which we can obtain sharply defined and undistorted shadows from a source of ordinary light. The target of the X-ray tube must be carefully centred over the most important part of the object and the rays must fall perpendicularly on to the film. Obliquity of the rays would produce a distorted shadow, which might give a meaningless or a deceptive radiograph.

Since we have only a simple shadow of the different parts of the specimen, there is nothing in a radiograph to tell us how far below the surface a flaw or a hidden inclusion is situated. Sometimes the object may be turned round and a second radiograph made at right angles to the first, but frequently this is not possible. Stereoscopic methods must then be resorted to. Two radiographs are taken from slightly different positions by simply sliding the tube a few inches to one side between the two exposures, and the two resulting pictures are viewed together in a stereoscope. An impression is thus obtained of the different parts of the object standing out in relief, from which the depths can be judged. The actual depth of any inclusion can be calculated by very simple geometrical

means from the difference in position of its shadow in the two pictures if the original distance from the tube target to the film has been measured. This is the principle of the many methods of locating the position of bullets or other foreign bodies in the human frame which have been so much employed in war time radiography.

Sometimes an object is so varied in thickness or in X-ray opacity that it is impossible to obtain a satisfactory radiograph in one exposure. The radiation through the thin part would be so intense as to completely blacken the film in the time required to give sufficient exposure to the thicker part. In some cases the thin part can be screened by covering it with thin sheet lead, say $\frac{1}{32}$ or $\frac{1}{16}$ of an inch thick, or sheet brass of greater thickness may be used. A proportion of the rays get through this screen, but are so diminished in intensity that the time required for the correct exposure is the same as the time required for the thicker part. Sometimes this is not feasible, and it becomes necessary to radiograph an object in two or three different portions, as was done in the case of the German ærial bomb illustrated in Fig. 22. The nose was of thin sheet metal, the body a hollow metal tube filled with explosive compound of no great opacity to the rays, and the head was of the same outside diameter, but containing a fuze of almost solid metal. There were thus three areas, each requiring different conditions of exposure. The result of radiographing the body and head together is shown. The body is correctly exposed, but little detail is displayed in the head. A separate radiograph with rays of far greater penetrating power reveals the construction of the fuze.

This question of the correct exposure conditions is one of the most troublesome factors in successful radiography and calls for a great deal of experience, for it is not easy to reduce it to any general or simple rule which will fit all cases. If an X-ray tube produced rays of a simple definite



Fuze and Body of Bomb Point of Bomb

FIG. 22. RADIOGRAPHS OF A GERMAN AERIAL BOMB

wave length, or hardness, corresponding to the voltage at which it was operating things would be simpler. The voltage however, only controls the *maximum* hardness of the rays produced—the quantum limit referred to on page 108.

Even when the tube is worked at a perfectly steady voltage it gives out a mixture of rays ranging from very soft up to this maximum; that is to say, a mixture of wave lengths which would form a continuous X-ray spectrum. This is termed the general, or very often, from the analogy with the visible spectrum, the white radiation. The cause of it is that the electrons are not all stopped immediately they reach the target of the tube—some of them penetrate farther into it than others, so that the rate at which they are stopped is very varied. When the electron speed is sufficient to produce the characteristic radiation of the metal of which the target is made these characteristic rays are produced and added to the general radiation. With a tungsten target this begins to occur about 70,000 volts, and at 100,000 volts the tungsten characteristic radiation forms a very large proportion of the total X-ray output of the tube. The average, or what may be termed the effective, hardness is thus brought up considerably nearer to the maximum hardness by the presence of the characteristic radiation.

When we use these mixed X-rays to examine, say, a thin sheet of aluminium, only the very softest are absorbed —the remainder pass through to the film. If heavier metal, such as iron, is used, the emergent radiation will contain still less of the soft rays, and when we come to large thicknesses of iron, nothing but the hardest rays will get through in any appreciable quantity. When it is remembered that the soft rays are more easily absorbed by the film than the hard rays, it is seen that the effect produced on the film is the result of several variable factors— the tube output, which is varied by the type of electrical apparatus employed, the variable absorption of the

different rays by the specimen, and the absorption of the rays by the film itself. With so many changing factors it is not easy to specify the best conditions under all circumstances, and exposures which may be correct on one installation will not always give the same results with different apparatus.

The maximum thickness of mild steel through which it has so far been found practicable to obtain a satisfactory radiograph is 4½ inches, and this requires the tube to be operated at 300 K. V. with a current of 5 milliamperes for about an hour. Fig. 23 is a radiograph taken under these conditions, the arrangement of the specimen being shown in Fig. 21. The shadow of a lead cross placed on top of the steel (the film was underneath) is clearly shown, as is also a hole 0.3 inch deep in the centre of the steel. With 200 K.V. radiographs of steel up to 2 inches thickness can be obtained with short exposures of less than a minute, and up to about 3 inches with exposures of 30 minutes or more. As an indication of the kind of exposures required Fig. 25 shows some of the exposure conditions which have been found to give satisfactory results at the Research Department, Woolwich. They show the exposure in milliampere-seconds for various thicknesses of steel with various voltages up to approximately 200 K.V. A very general current at which to operate a tube is 5 milliamperes, so that dividing the exposures shown by 5 gives the usual time required in seconds. These exposures are the result of practical tests, and are such that a variation of 3 per cent. in thickness in the specimen can be distinguished with certainty in the resulting radiograph. Visual examination with a fluorescent screen can be made with 200 K.V. up to a thickness of about ¾ inches, and differences of thickness of ⅛th of an inch upwards can be distinguished. For brass the possible thicknesses are considerably less because of the higher atomic weights of copper and zinc. A useful working rule is that brass

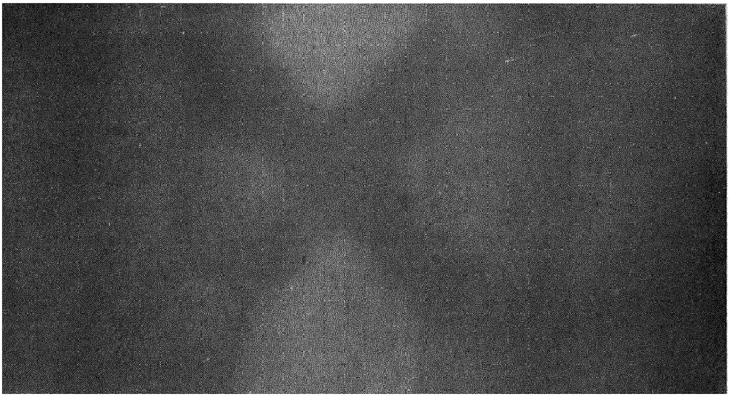


FIG. 23. A RADIOGRAPH THROUGH A BLOCK OF MILD STEEL 4½in. THICK OBTAINED IN THE RADIOLOGICAL LABORATORY, WOOLWICH
This represents a record in the X-Ray penetration of steel

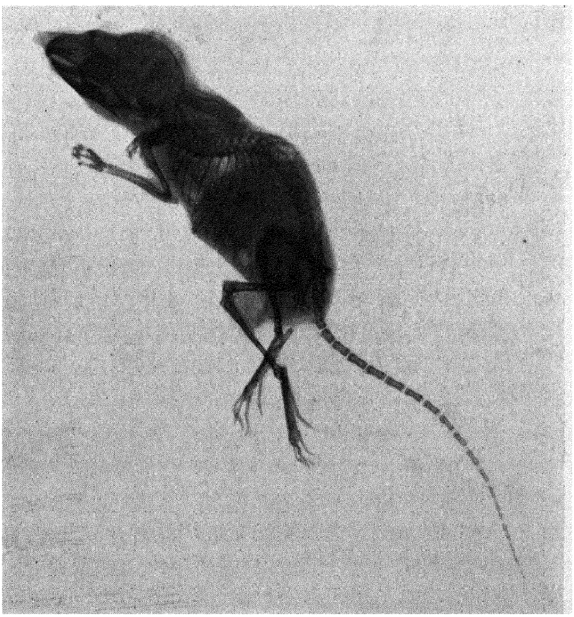


FIG. 24. RADIOGRAPH OF A YOUNG MOUSE TAKEN WITH THE SAME APPARATUS AS FIG. 23

requires the same conditions as steel of 50 per cent. greater thickness.

The full significance of these figures is perhaps only fully appreciated when we examine and attempt to handle a slab of steel 4½ inches thick. We then begin to realise the marvellous penetrating power of these hard rays, and also the progress that has been made, for in the year 1918 one

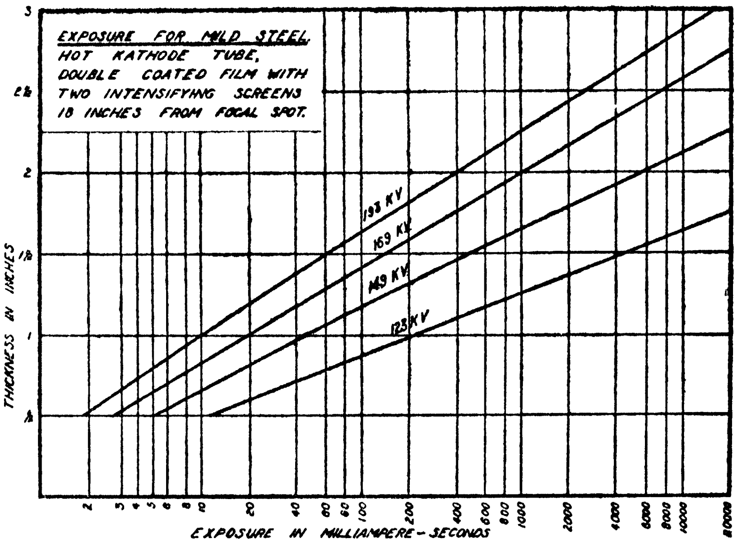


FIG. 25. SPECIMEN OF PRACTICAL EXPOSURE CHART AS USED IN THE RESEARCH DEPT. WOOLWICH.

inch of steel represented the utmost limit of radiographic possibility. As a contrast showing the wonderful adaptability of a modern X-ray installation we have Fig. 24, a radiograph of a young mouse, taken with the same apparatus as the radiograph of the block of steel.

So far, although we have mentioned the scattering that takes place from the air and surrounding objects, nothing has been said of the scattering which occurs in the specimen itself. When we radiograph, say, a piece of steel,

three things happen to the beam of X-rays which enters it—part is scattered, part is absorbed, and the remainder travels right through and passes out unchanged. Some of the absorbed part re-appears as the characteristic radiation of the atoms which have absorbed it, and this radiation is added to the rest of the scatter, but with steel, and in most practical cases, it is so soft that its effect may be neglected, since it will probably not even penetrate the film wrapper. It is the part of the original beam which travels right through the specimen and the variations in its strength from place to place, which impresses the radiograph on the film. Some of the scattered part must also reach the film, but since it consists of rays scattered and re-scattered in all directions, it will cast no definite shadow and will merely tend to produce a more or less uniform fog all over the film.

The radiographs shown here and the results quoted have all been obtained without any attempt to minimise the effects of these scattered rays. From the quality of the results it might be thought that their effect is but trifling. This is by no means true, particularly when we come to use very hard rays or when we radiograph a large thickness of some material of low atomic weight. In either case the scattered rays can travel a good distance through the substance without much loss, so that a large proportion of them are able to emerge from the interior and reach the film which, although rapidly blackened and apparently fully exposed, shows little detail.

This difficulty was experienced in medical radiography when dealing with the thicker parts of the human body, and to meet it the Potter-Bucky diaphragm was introduced with vastly improved result. Similar diaphragms are now being used for industrial radiography in many cases, and, as will be seen later, are likely to become an essential with the super-hard rays which it is hoped to produce in the future. The Potter-Bucky diaphragm con-

sists of a number of parallel strips of thin lead placed edge on *between* the specimen and the film (See Fig. 26). They are all arranged radially along the circumference of a circle, and so pointing to the focal spot of the tube which is placed at the centre of the circle. This is clearly seen from the diagram, from which it is apparent that the original direct beam can pass unhindered between the lead grids,

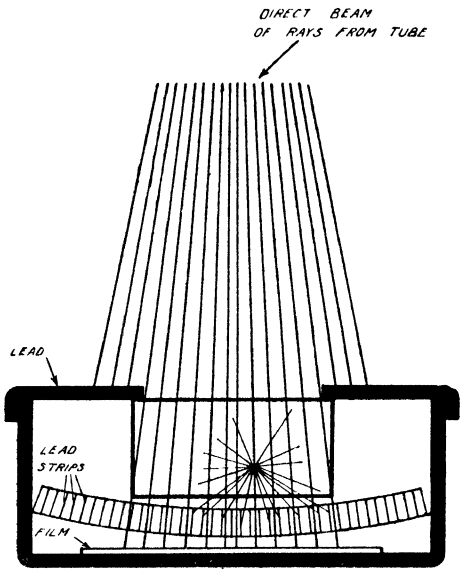


FIG. 26. DIAGRAM ILLUSTRATING USE OF A GRID DIAPHRAGM

but that a large proportion of the scattered rays are stopped by them. The proportion that is stopped increases as the ratio of the depth to the spacing of the grids increases. Good results are obtained in industrial work with a ratio of 6 or 8 to 1, and a convenient size is a depth of one inch and a spacing of $\frac{1}{8}$th of an inch between the grids. For strength the space between the grids is usually filled in with some substance such as wood or celluloid, which offers little opacity to the rays. It will be realised

that this arrangement must result in a series of narrow lines—the shadows of the grids—across the radiograph. By making the diaphragm travel during the exposure at a uniform speed across the film (at right angles to the length of the grids) each part of the film is covered in turn for

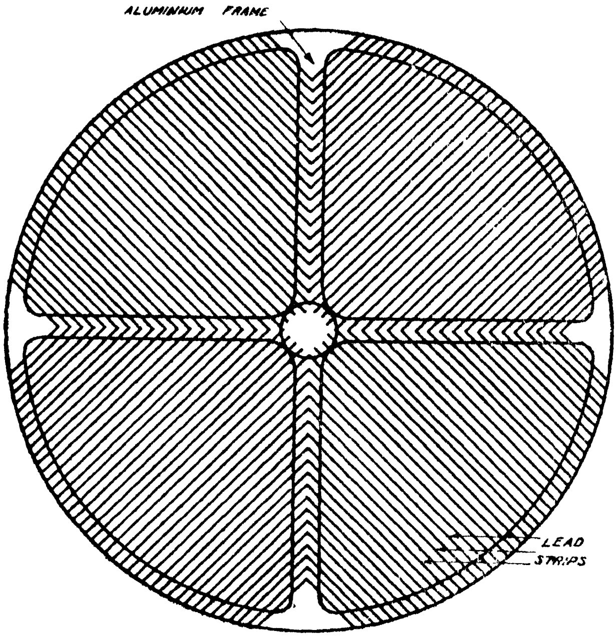


FIG. 27. A NEW EXPERIMENTAL TYPE OF ROTATING GRID DIAPHRAGM DESIGNED IN RADIOLOGICAL LABORATORY, WOOLWICH.

the same time by each grid, so that no shadow results. The mechanism for this is not simple, but the arrangement is used in most modern medical installations. Grids in the form of a flat spiral have been made which leave no shadow if kept rotating at a steady speed, but their construction is difficult. The latest grid of the rotating type, designed at Woolwich and now being experimented with, is shown in Fig. 27. One great advantage of a rotating grid is that its

motion may be maintained throughout any exposure, however long.

The Potter-Bucky diaphragm in the parallel grid form that has been described is of great value, but it cannot have any effect in reducing scatter in directions parallel to the grid. It was originally introduced in America by Dr. Bucky with double grids, the second set crossing the first at right angles, so that they formed small radial cells. This form of double grid has not found favour for medical work, because it is not easy to get rid of the shadow of the grids, but it is far more efficient than the single form.

The use of a moving grid necessitates a slight increase in the exposure to balance the time the film is covered by the grids. With a fixed grid, this does not apply, of course. It is found, however, that a film is much less dense when exposed with a grid than if it is exposed without one for the same time. The loss of density is due to the removal of the general fog caused by the scattered rays. With this unwanted blackening removed, the useful rays may be allowed to operate until the film has received its correct exposure, which is the exposure at which a definite difference of intensity produces the maximum contrast, so that finer and more distinct detail will be shown. With a good film the contrast remains fairly constant over a considerable variation of exposure, so that there is a reasonable latitude in the matter of the "correct" exposure.

This brings us to the question of the best conditions of penetration and exposure, a consideration of vital importance for the production of a successful radiograph either with or without a grid. We may vary the current through the X-ray tube, the distance of the film from the tube or the actual duration of the exposure, but, from this point of view, changing any of these has the same effect—an alteration in the exposure. Our whole control, then, is really limited to two factors, the exposure and the penetrating power of the rays employed.

Thicker specimens will obviously require rays of greater penetrating power, but since a radiograph is usually required to show the smallest possible detail, which amounts to the same thing as saying the smallest possible difference in thickness, mere penetration is not the only thing required. It is necessary that the rays which *have* penetrated shall show an appreciable variation in intensity for a small variation of thickness and also that the exposure shall be such as to produce the biggest possible contrast in the amounts of blackening of the film produced by these varied intensities; that is to say, that the exposure shall be correct from the point of view of the film. If very penetrating rays are employed a great deal of radiation will get through and the blackening of the film will be rapid, but there will be little difference resulting from a small difference of thickness—the variation between say 2 inches and $1\frac{15}{16}$ inches will be trifling. On the other hand, soft rays will be strongly absorbed and but little will get through, so that the blackening of the film will be slow, but there will be a much bigger difference in intensity resulting from a small change of thickness.

The suggestion has often been made that if only sufficiently soft rays are employed it should be possible to show in a radiograph any minute difference in thickness (or any difference in opacity), however small. This would be true if scattering could be completely eliminated and if exposures could be prolonged for an indefinite time—two conditions which are impossible in practice. We can largely reduce the scattering by means of a grid diaphragm. Let us suppose for the moment that we can get rid of it completely. Our only limitation then is in the matter of time. We must take some arbitrary time as the practical limit of exposure and expose at some voltage which will produce rays hard enough to allow sufficient radiation to pass through the specimen in the time available to give the film its correct exposure, but at the same time

the rays must be soft enough to show a reasonable difference of absorption for a small change of thickness.

It is obvious that there must be some optimum voltage at which the best compromise between the various factors is produced. This has been investigated at Woolwich on theoretical grounds by A. G. Warren, who finds that for thick specimens of steel, say, from 2½ inches upwards, this optimum voltage is far in excess of anything we are able to use at present, even allowing as much as one hour as the limit of exposure time.

We know, of course, that if we exposed three inches of steel for an hour or even considerably less with an extremely high voltage without a grid the film would be hopelessly blackened by the scatter, and from this we get an indication of the magnitude of the scatter at these high voltages. Experiments were therefore made with a view to obtaining some information as to the amount of the scattered radiation. It was found that though the total amount of scattering was very large and increased with the hardness of the rays, the actual amount of scatter in any particular direction was small. In other words, it is the combined action of all the scattered rays from all possible directions that causes the blackening of a film. A comparison was then made of the exposures required to produce the same effect on a film when exposed through two similar blocks of steel, in one case allowing all the scatter to operate, but in the other cutting out practically all of it by interposing a long tube of lead between the steel and the film. This would act like a single cell of a double grid diaphragm. It was found that for 1 inch of steel exposed at 170 K.V. the scatter *reaching the film* was three times the amount of the direct beam (the rays which had travelled straight through). With 2 inches of steel at 200 K.V. the scatter had increased to eight times the direct emergent beam, but this was only about 5 per cent. of the *total* scatter. At this voltage, therefore, a large

part of the scattered radiation must be absorbed and unable to reach the film. In the case of three inches of steel at 200 K.V. the scatter reaching the film is probably of the order of 25 times the direct rays getting through, but still good definition is obtained.

Now, it had been recognised for many years that Thomson's theory of scattering by no means agreed with all the experimental facts, and in 1923 Compton introduced his quantum theory of scattering based on the work described at the end of Chapter VIII. Although still not agreeing with all the known facts, this theory is much more in accord with the results of experiment. It explains the increase of scattering with the hardness of the rays and also suggests that the scattered rays become more concentrated in a forward direction—that is to say—towards the direction of travel of the direct beam as the hardness increases. As a result, the alarming suggestion has been put forward by some authorities that with increasing voltage a limit will soon be reached when the scattering will have increased so much that practically the whole of the primary beam of rays will be scattered, and no definite shadow will be produced on the film. If this were so it would set a very definite limit to the possibilities of radiological examination, and continued research into the use of higher voltages and harder rays would be useless. Fortunately an examination of the experimental facts, together with a full consideration of Compton's theory, does not uphold this dismal view.

We may regard three inches of steel as the practical limit of radiography with 200 K.V. From Compton's work we find that under these conditions only $\frac{1}{2500}$ part or .04 per cent. of the original radiation reaches the film as a direct beam, but still we are able to obtain a radiograph with moderately satisfactory detail, and this without the use of a grid, although, as was said above, the scatter reaching the film is something like 25 times the direct

beam or 1 per cent. of the original radiation. When we come to radiograph very much thicker specimens we must increase the voltage so that no less than .04 per cent. of the original beam penetrates to the film. With increasing voltage the scattering is going to increase. Let us imagine the worst possible (but improbable) case. Let us suppose that with a very high voltage the whole of the remainder —the other 99.96 per cent—is scattered, and, to make matters still worse, we will suppose that the whole of this scatter is occurring in a forward direction towards the film. Are we now to assume that the whole of it would reach the film ? If so, we should have practically 100 times as much scatter affecting the film as in the case of the three inches of steel, and the chances of obtaining a useful radiograph would seem to be remote.

Fortunately Compton's theory suggests that such a state of affairs is very improbable. Compton regards scattering as due to the collision of a quantum with an electron, the quantum proceeding on its way as was explained on page 107, with diminished energy, which is the same thing as saying with lower frequency or a longer wave length—that is, as a less penetrating ray. Scattering then on this theory has two important consequences. In the first place the quantum loses some of its energy, which means that some of the energy of the X-ray beam no longer appears as X-rays—in other words some of the rays have been absorbed in the scattering process. Secondly, the scattered rays are less hard than the original rays. The loss of hardness has been experimentally observed, and this part of the theory is confirmed, but the absorption which the theory associates with scattering has not yet been detected in the case of X-rays, although it has been found with the γ-rays from radium. It is probable that this part of the theory will also receive confirmation when harder X-rays are experimented with.

What is the effect of all this on our attempt to radiograph a very thick specimen by the use of extremely high voltages ? Compton's theory indicates that this absorption due to scattering should increase with the hardness of the rays, until, with infinitely high voltages, half the total energy is so absorbed. Instead of having to contemplate the possibility of the scatter which reaches the film being 100 times that to which we are now accustomed, we may reasonably assume that the result of this absorption will be to reduce it to somewhere near 50 times. Then, again, the loss of hardness of the scattered rays, which should be considerable with very high voltages, will tend to diminish their chances of reaching the film, so that on this account we should obtain a still further reduction of our figure, and we may therefore predict that in the worst possible case the effect of scatter should not be more than 50 times the present value. That it would ever rise to anything like this amount is improbable. Our supposition that the *whole* of the scatter might reach the film is particularly improbable, as the forward concentration of the scatter only occurs to the extent indicated by the theory with thin specimens. Experiments made in the Research Department show that the distribution of the scatter tends to become more and more uniform as the thicknesses of the specimen increases.

We are left, then, with this figure of 50 times the present value as the possible (but not probable) maximum limit of scatter. So far we have not considered the use of a grid. Will a grid deal with this large amount of scatter ? Warren has worked out the theory of the grid diaphragm and finds that a double grid of 1½ inches depth and ¼ inch spacing, should, under practical conditions, reduce the scatter passing from the specimen to the film to about 1 per cent. In fact, if the distribution of the scatter is uniform it should be reduced to ½ per cent. The result, then, suggests that, in the worst possible case we can

imagine, the effect of scattering, if we use a grid, should be rather less than we now experience when radiographing 3 inches of steel without a grid, so that we may hope to obtain at least as good detail as we get at present through any thickness of material when we can produce sufficiently penetrating rays. It is quite possible that the scattering may prove to be very much less than we have imagined, and then by the aid of a grid we shall be able to approach more nearly to the condition of optimum voltage already described, and so obtain a rendering of fine detail such as is at present impossible.

Prophecy is proverbially unsafe, and is particularly dangerous when it relies on a new and only partially established scientific theory, and any forecast of the thicknesses through which practical radiographs will be possible when higher voltages can be employed must be taken as being highly speculative. All that can be said is that, taking the absorption for very hard rays as calculated from Compton's theory, and allowing for the increase of efficiency of an X-ray tube with increasing voltage, we obtain as a maximum practical thickness of steel, 4.5 inches with 300 K.V., 5.6 inches with 400 K.V., 6.8 inches with 500 K.V., and 8.1 inches with 600 K.V. As far as we have gone at present, that is to say, up to 4.5 inches results agree with the figures given by the theory, and it can only be hoped that if any modification is found necessary at higher voltages it will be in the direction of increasing thickness rather than the reverse.

We have dealt here with the radiography of steel, but the same considerations apply to the examination of thick specimens of other metals, and also to their visual examination by means of the fluorescent screen. Although we may never be able by visual means to deal with anything like as great a thickness as can be examined by radiography, it would seem that the more penetrating we

can make our rays the greater will be the possibilities for the use of the fluorescent screen. We can, then, continue our research after higher voltages and harder rays, secure in the knowledge that, whatever difficulties we may encounter, we are at any rate not striving after the impossible.

CHAPTER XVII

X-RAYS IN INDUSTRY

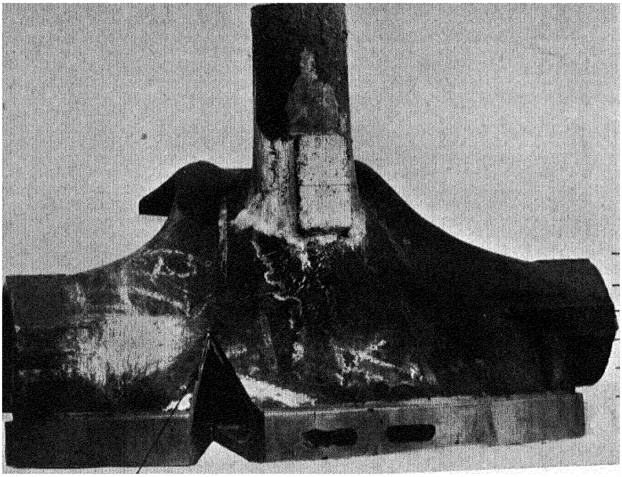
MANY and varied are the uses to which X-rays have already been applied. From golf balls to aeroplanes, from chocolates to big guns, from the fitting of shoes to the detection of " faked " oil paintings have their applications ranged in the comparatively few years during which industrial uses have been a practical possibility. No great power of imagination is required to realise the immense importance to many industrial processes of the ability to see into the interior of either the raw material or the finished article in order to make sure that all is as it should be. In these days of expensive labour a hidden defect in raw material, which may only be revealed after a great deal of work has been done on it, may prove disastrously costly. Such hidden flaws occur, especially when the raw material is metal, far more frequently than the layman imagines. Then again, many finished articles depend for their correct functioning, or it may be for their safety or their reliability or their life, on the complete or correct assembly or the perfect fit of one or more internal components. Frequently, elaborate systems of inspection and control are set up to check at every stage the assembly of important pieces of mechanism, and yet, such is the frailty of human nature, even with the most ingenious and so-called infallible systems, mistakes do sometimes occur. It has even been known that the inspection of one stage of the assembly has upset the correctness of some

component passed as correct at an earlier stage. It may be argued that this is the fault of the system of inspection. Be that as it may, there is always the final assembly of the last component to be checked, and usually there is no way of inspecting that except by the somewhat drastic method of taking the whole thing to pieces again or by cutting it up.

Take the simple case of a golf ball. Most golf balls contain a dense central core. Nobody would think of using a golf ball of which the exterior was not perfectly spherical. It is equally important that the heavy core should also be a perfect sphere, but until the use of X-rays was thought of even the most careful manufacturer could not be sure that the core had not been distorted in the final stages of manufacture. All he could do was to cut up (and so destroy) a certain percentage as a check on his methods and hope for the best with the remainder. Nowadays certain manufacturers inspect their whole output by the simple method of allowing the balls to roll between an X-ray tube and a fluorescent screen.

Metal castings of all sorts form a class of article which can only be inspected for hidden defects by destructive methods if X-rays are not available. The same thing applies to welding of metals. As the late Director General of Factories at the War Office once remarked, destructive methods of inspection are " like striking a match merely to see if it is a good one." X-rays do provide us with a means of seeing into and learning a great deal about the interior of many articles without destroying or in any way harming them. Therein lies the immense value of the application of radiology to industry—a value which is only now beginning to be realised and which is every year being more appreciated in the commercial world.

Castings perhaps will provide one of the most extensive fields for radiological inspection. Castings of all sorts and sizes and in all metals are used in every branch of engineer-



Flaw FLAW SHOWN IN RADIOGRAPH

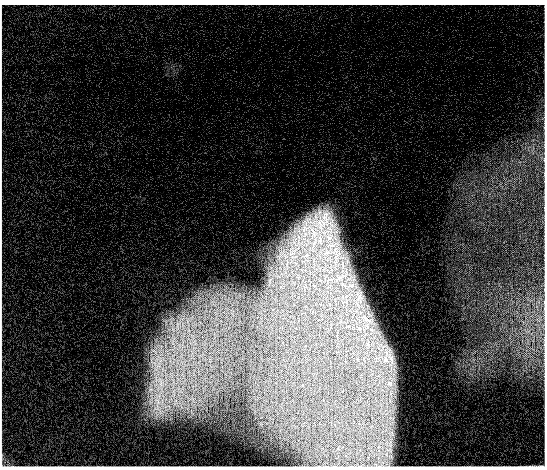


FIG. 28. HIDDEN FLAWS SHOWN IN A RADIOGRAPH OF A STEEL CASTING

ing work, and only the engineer knows with what distressing frequency they contain cracks and blowholes, as the large internal cavities are called. Sometimes there is ample evidence of these defects on the surface, sometimes none at all. More frequently a casting will show some slight signs of possible faults on the surface and the harassed engineer is left in doubt as to whether he is confronted with mere superficial markings or whether the apparently trifling defects widen out into large fissures or cavities in the interior of the metal. Many important and expensive castings are scrapped because he dare not take the risk. A simple X-ray examination would settle all doubt in many of these cases.

An example of large flaws existing in a casting without any external evidence is shown in Fig. 28, a radiograph taken in the Research Department, Woolwich. The casting was afterwards cut through the part indicated as faulty and the flaws revealed as shown in the ordinary photograph. At Woolwich the whole output of certain important castings is radiographed before any expense of machining them is incurred. Castings of less importance are radiographed when doubtful cases arise. In some factories, the first batch of castings from a new design is radiographed. If faults are found modifications are made in the design or the method of casting until radiography shows that the defects have been eliminated before the design is taken into use.

Not every casting can be completely radiographed, for occasionally the shape is too complicated. Usually, however, it is possible to deal with the vulnerable parts, and this is all that is necessary in most cases. In any case, X-ray examination is generally confined to the important areas in the interests of economy in film, which is the chief item of expense. Expense, however, in a matter of this sort is merely relative and usually trifling. The cost of X-ray film is just under a farthing per square inch

An expenditure of ten shillings on film has been known to save as much as £60 worth of useless machining on one casting alone!

Another valuable result which the general introduction of radiological inspection will bring about is a reduction in the size and weight of castings. In the past designers have been compelled to allow a far bigger margin of safety than is really necessary, owing to uncertainty as to the soundness of their castings.

Fig. 29 shows how numerous the flaws may be in a heavy casting, and Fig. 30 illustrates the development of cracks. The depth of such cracks can be estimated either by stereoscopic methods or by density measurements on the negative. Defects in a manganese bronze casting are illustrated in Fig. 31, and "sponginess" in a cast brass ingot in Fig. 32. Sheet brass is prepared by rolling out these cast ingots, which are usually between one and two inches in thickness, and any holes or defects are necessarily retained in the rolled out metal. Radiography has been extensively used as an aid to general research in the production of sound brass castings. It is in this way, as an additional research weapon, that X-rays should be of the greatest value to the foundry engineer. A routine inspection of all castings, except in specially important examples, would be too big an undertaking, but as an adjunct to research and as a check on new designs, X-rays are far too valuable to be ignored.

It is often imagined that forgings, as contrasted with castings, are bound to be free from internal flaws. X-rays have shown that this is by no means always true, and the examination of important forgings by radiography is certainly worth while. Fig. 33 is a radiograph taken at Woolwich through a portion of a very large cylindrical steel forging. Certain suspicious markings were noticed on its inner surface, which the radiograph showed to be the beginnings of a deep and very extensive flaw. Its depth

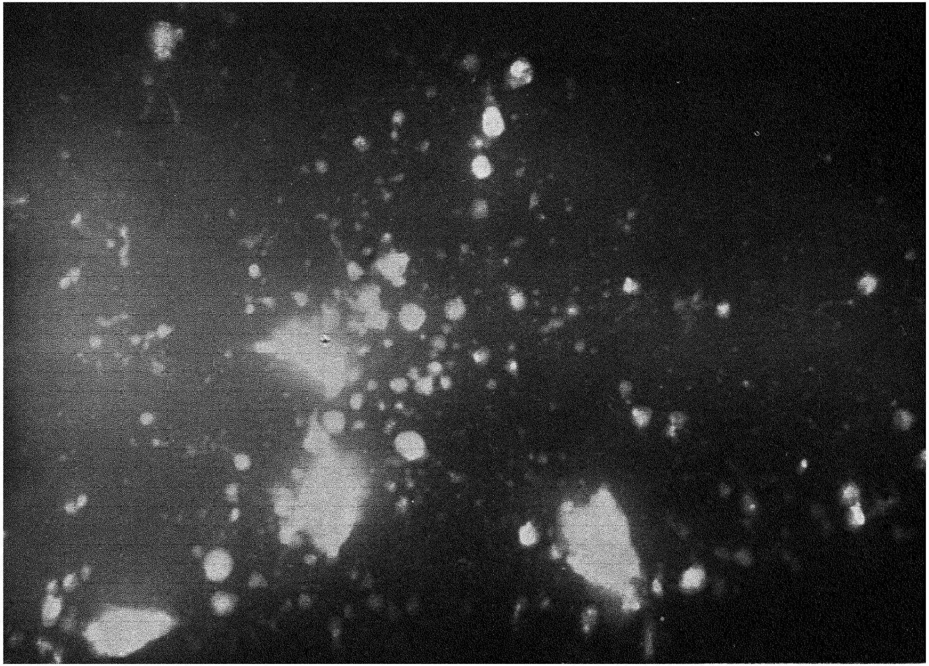


Fig. 29. Radiograph of a Heavy Casting Showing Numerous "Blow-holes"

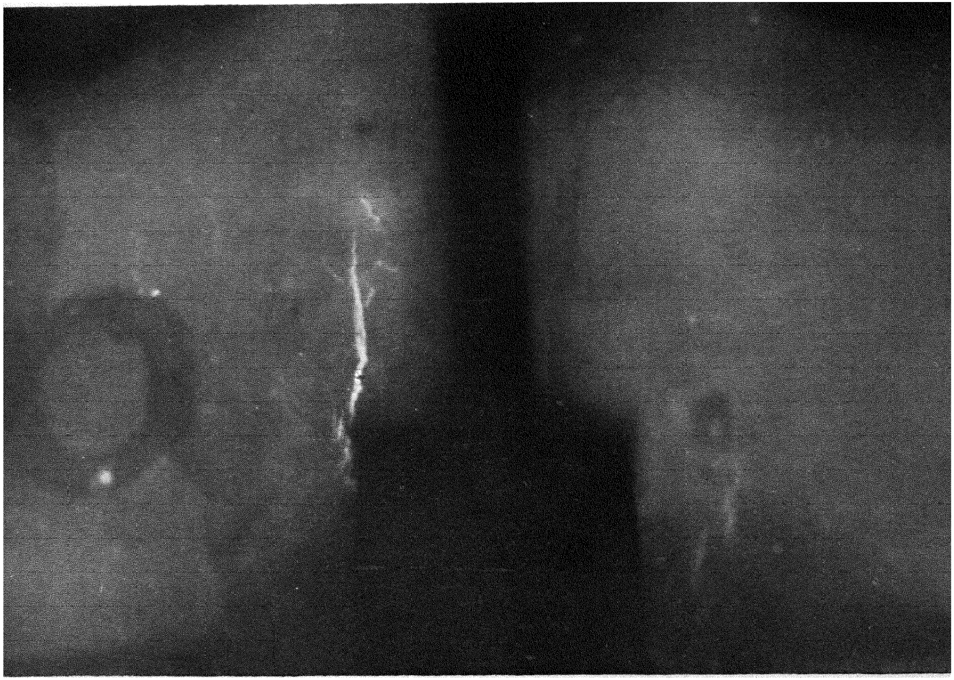


Fig 30 Radiograph Illustrating Cracks in a Casting

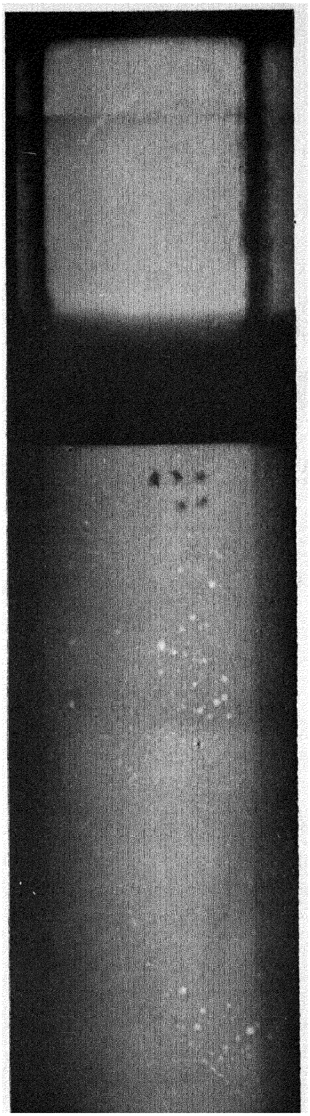


FIG. 31. RADIOGRAPH OF A CYLINDRICAL CASTING IN MANGANESE BRONZE
The five black spots are lead paint marks on the surface

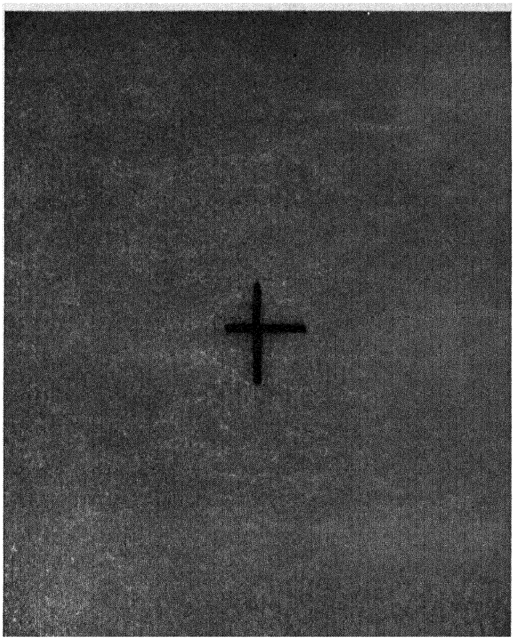


FIG. 32. RADIOGRAPH SHOWING "SPONGINESS" IN A CAST BRASS INGOT $1\frac{3}{8}$in. THICK

The dark cross is the shadow of a lead marker placed on the surface to indicate the position of the radiograph on the ingot.

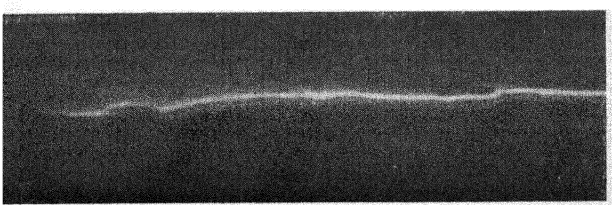


Fig. 33. RADIOGRAPH SHOWING PART OF A DEEP FLAW IN A LARGE CYLINDRICAL FORGING

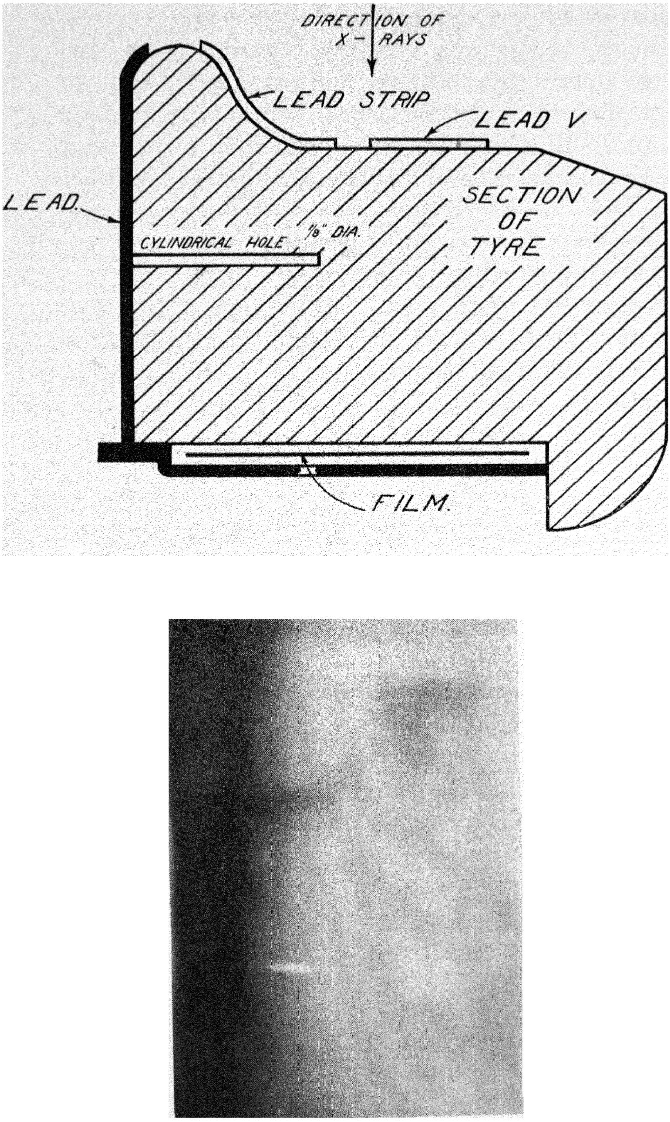


FIG. 34. RADIOGRAPH OF PART OF A RAILWAY LOCOMOTIVE TYRE showing an artificial internal flaw $\frac{1}{8}$th inch diameter

was estimated by stereoscopic means to extend as much as two-thirds of the way through the wall in the worst parts. Very definite flaws have been revealed at Woolwich in radiographs of some important forgings of tungsten steel of an inch in thickness. The presence of heavy tungsten atoms in steel greatly increases its X-ray opacity, of course, so that the exposure required is very much greater and the maximum thickness that can be examined much less than for ordinary mild steel.

The smallest size of flaw that can be shown in a radiograph is a matter of great practical importance. Even with thick steel specimens a flaw which reduces the total thickness of metal by only 2 per cent. or 3 per cent. is quite easily recognised. With special precautions, such as the use of a grid diaphragm, and in thinner specimens, much smaller flaws are revealed. A 3 per cent. flaw is well shown in Fig. 34, a radiograph of a railway locomotive tyre. An artificial flaw was made in this tyre by drilling a hole of $\frac{1}{8}$th inch diameter in the centre of it. The illustration shows, above the radiograph, a section of the tyre and the position of the flaw, together with various lead markers used for localising its position. Above the radiograph is shown the thicknesses that have been penetrated. In the original negative the $\frac{1}{8}$th inch flaw is quite definitely shown through all thicknesses up to 4 inches, but a certain amount of contrast is lost in the reproduction. The vital importance of the soundness of railway tyres was very strikingly emphasised by a railway accident that occurred a few years ago. In that case a defect of very considerable dimensions was found. The radiograph illustrated here was made to prove the possibility of detecting by radiographic means any flaw of a size likely to be dangerous.

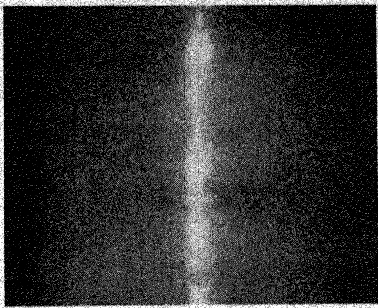
Another class of work in which X-rays provide the only non-destructive method of inspection is the comparatively modern art of welding metals either by the electric arc or by the oxy-acetylene flame. Although welding is con-

siderably employed, it would have a vastly extended sphere of usefulness if it were not for the fact that the strength of a weld depends so greatly on the skill and the care taken by the workman in making it. An unskilled or a careless workman can easily produce a superficially sound weld with no real union of the two parts below the surface, and this state of affairs can only be revealed by means of a radiograph.

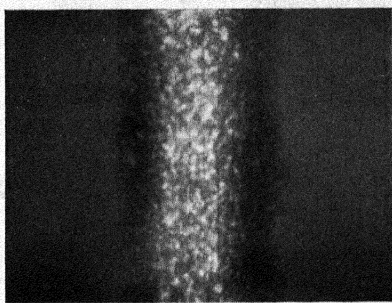
A series of experiments has been carried out at the Radiological Laboratory, Woolwich, to test the value of radiography in the examination of welds in steel. A large number of welds in different thicknesses of steel plate and in various steel objects, made under ordinary conditions in several different workshops were radiographed and afterwards sectioned and tested by ordinary mechanical means. It was found that anybody with reasonable experience in the interpretation of radiographic results could quite readily classify the welds as sound or faulty from an inspection of the radiographs. Those of which the strength, as ascertained by mechanical tests, fell below 80 per cent. of that of the unwelded plate were detected unmistakably, whilst there was sufficient evidence to cast suspicion on all below 90 per cent.

It is sometimes found in welding that the original metal near the weld is weakened by the heating it receives during the welding operation. Unfortunately a radiograph gives no evidence of this, but since it is due to changes in the crystalline structure of the metal it is probable that it will ultimately be found possible to take a few filings from the metal near to the weld, examine them by the new methods of X-ray spectroscopy and so detect any harmful change.

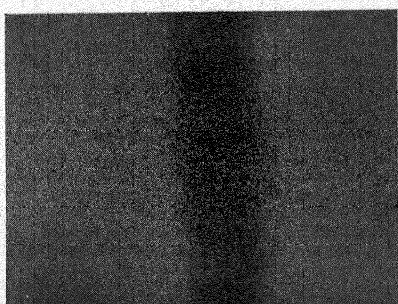
Welding is of immense importance in aeroplane construction. Fig. 36 is an example of an apparently sound weld in an aeroplane part which is shown by X-rays to be merely superficial. The light line shows that there is no



A very bad weld. Strength only 17 per cent. of that of the unwelded plate



A poor weld in plating 1in. thick. Strength 74 per cent. of that of unwelded metal.



A good weld. Strength 100 per cent.

FIG. 35. RADIOGRAPHS OF WELDS IN STEEL PLATE

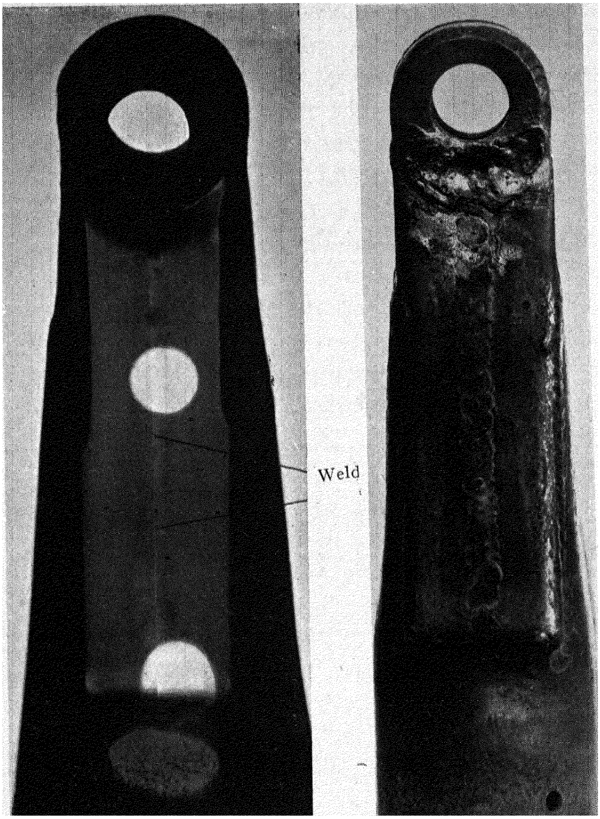


FIG. 36. PHOTOGRAPH AND RADIOGRAPH OF A WELD IN A STEEL AEROPLANE FITTING

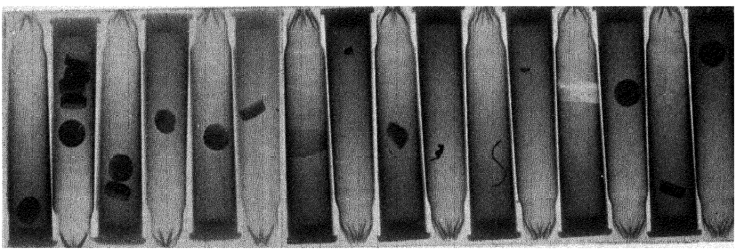


FIG. 37. RADIOGRAPH OF FAULTY BLANK AMMUNITION

real union between the two pieces of metal. Aeroplane and airship parts are, of course, particularly suitable and comparatively easy subjects for X-ray examination on account of their lightness. The new method proved of great value during the war, and is now being made extensive use of. A picture of a special X-ray set designed and made at Woolwich for this work is shown in Fig. 19. Flaws in aluminium parts are readily detected and timber is very easily examined. Internal knots, worm holes and resin pockets are revealed and the quality of hidden workmanship can be checked. The importance of all this in aircraft construction cannot be over-estimated. A great deal of this class of work can be done with an X-ray outfit of only moderate power, and much use can be made of the fluorescent screen. It may be remarked here that whenever a fluorescent screen is used for the purpose of industrial X-ray work it should be covered with a very thick layer of lead glass to absorb the X-rays which pass right through the screen, and even then should never be viewed directly, but always by means of a mirror.

X-ray methods have now been applied on a practical scale to a great number of Service uses. Perhaps the simplest of these is the examination of blank ammunition, which is very easily dealt with visually by the fluorescent screen. Many millions of rounds, including all the ammunition for the Royal Naval and Military Tournament, have been inspected by X-rays. That this is not by any means a superfluous precaution is shown by Fig. 37, which reveals the contents of some of the rejected cartridges!

The use of X-rays for Service inspection purposes demands in many instances that large numbers of exactly similar small articles shall be dealt with expeditiously. In the case just referred to the cartridges are laid by boys in thin wooden or millboard trays, which are passed beneath the fluorescent screen. Nearly 20,000 an hour are inspected with one X-ray set. When visual methods are not suffi-

cient the procedure is slightly less simple. As an example, the case of certain important detonators which cannot be adequately inspected by any other means may be quoted. 100 per cent. inspection of these articles is carried out by radiography before they are passed into service, as the detail that has to be looked for is too fine to be distinguished with certainty on a screen. In the interests of economy, photographic film is not used, as it is found that a radiograph taken direct on to photographic bromide paper, which is far cheaper than film, gives all the definition required. A number of wooden holders are used, into which the detonators are packed in batches for radiographing. Each holder is marked with its own identification letter cut in lead, so that its shadow appears on the radiograph. The sensitive paper is carried in a lead holder so arranged that only a strip of the requisite width is exposed at one time. A filled holder is placed over this strip of paper, the X-ray tube is switched on for a few seconds, after which the holder is exchanged for another, the sensitive paper is pushed along to expose a new strip and a new exposure made. When the whole of the paper has been used it is developed and fixed—this operation taking about five minutes—and the detonators, which have meanwhile remained in the holders in which they were radiographed, are identified by means of the lead letters. In this way 800 or 1,000 an hour may be radiographed and sorted at a trifling cost for material.

The same principle is employed for the inspection of other articles, such as shell fuzes. Here, owing to the much greater thickness of metal involved, films and intensifying screens have to be employed, but the method remains the same. The fuzes are carried in holders arranged to fit around a semi-circular protective tube box, from which the X-rays can only escape through a narrow slit of the width of the fuzes. Exposure times vary from a few seconds up to about a minute, and some hundreds of fuzes

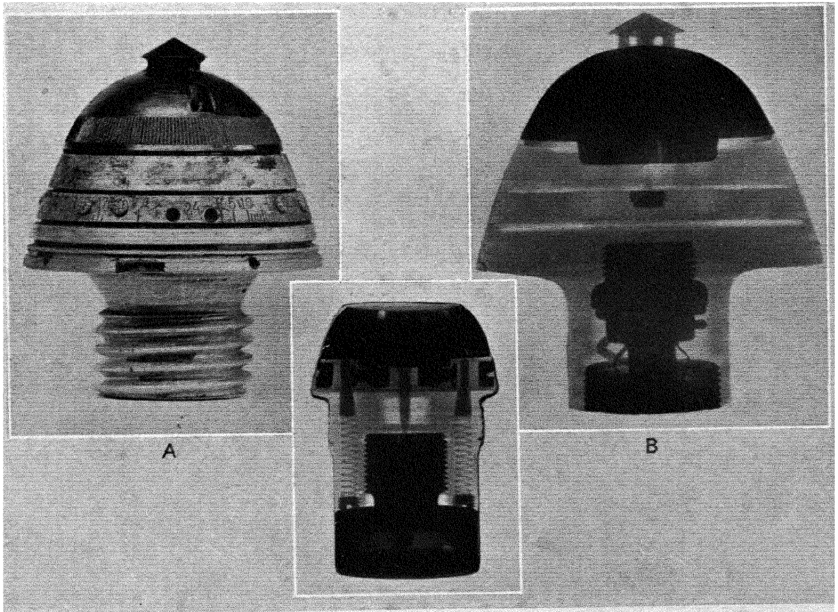


FIG. 38. RADIOGRAPHS OF SHELL FUZES
A is a photograph and B is a radiograph of the same fuze.

can be dealt with every hour. This X-ray method does not in any way supplant the ordinary methods of inspection, which have done such wonders in ensuring, even under war time conditions, the supply of reliable and safe ammunition, but it might be adopted as a valuable adjunct and final check to the older system. The X-ray method has been described here not only because of its general interest, as showing how every possible precaution is taken to ensure the efficiency and safety of all types of service stores and how every new discovery of science is made use of to that end, but also because the possibility of this form of "mass production" in radiography is not generally realised. If X-rays are to be of full value to industry, they must be applied on these wholesale lines, and apparatus must be so arranged that large numbers of articles may be dealt with rapidly and with certainty of result at a low cost. It is sometimes thought that X-ray apparatus is too fragile or too complicated for general use in manufacture in this way. Again a Service example may be quoted. It became necessary to know whether a very large number of nailed down ammunition boxes had been correctly packed. The expense of opening and re-nailing and labelling would have been considerable. X-rays did the job at a fraction of the cost. The apparatus used was made up into a portable form capable of being wheeled from storehouse to storehouse. Connected by a plug to the electric light mains it was controlled by the operation of a single switch.

An extremely valuable war time application of X-rays was the examination of foreign ammunition of unknown construction. Before the advent of metal radiography investigations of this sort were always hazardous undertakings, but with the use of X-rays a good idea of the general construction could always be obtained and usually the position of any detonator or particularly dangerous point could be located. An example of a German aerial

bomb has already been given in Fig. 22, and in Fig. 39 are shown a number of radiographs of explosive and armour piercing ammunition of foreign manufacture.

One other very valuable, but very different army use of X-rays must be mentioned—their application to veterinary surgery. A specially designed apparatus for this work was made at Woolwich and installed at the Army Veterinary School at Aldershot a few years ago, where it has been giving very valuable aid in the investigation of bone and other diseases of Army horses.

Considerable use has been made of radiography for the examination of electrical insulating materials. Many of these substances, such as mica, ebonite, or the various forms of compressed paper insulators, are liable to contain small particles of metal or metallic salts, which seriously detract from their value as insulators. X-rays can quite easily detect this defect (Fig. 40). Although this class of substance is usually very transparent to the rays, so that a fluorescent screen is brilliantly illuminated, radiography generally has to be resorted to because the metallic particles are too small to be recognised with certainty on the screen.

The strength of a glued wood joint is sometimes of importance, as, for instance, in aeroplane construction. It depends largely on the even distribution of the glue between the two surfaces. A very thin layer of glue has very little opacity to even soft X-rays, so that it is hardly shown in a radiograph, but it may be rendered visible by adding a small proportion of some inert heavy substance such as a lead salt to the glue before it is used. When this was first suggested it was thought that any such addition would ruin the adhesive power of the glue, but experiments in the use of small proportions of lead sulphate carried out at Woolwich showed that this was not the case. In fact, the addition of 5 per cent. or 10 per cent. of this substance to the glue appeared to result in a slight increase in the strength of the joint. The glue was rendered plainly

visible in the radiographs, as is seen in Fig. 41. The figures given represent the loads at which the joints broke on mechanical testing. It will be noticed that the strength increases as the glue is more uniformly distributed.

The impregnation with a lead salt of a material having little X-ray opacity may possibly be found to have many applications in industrial radiology. It has been employed at the Dunlop Research Laboratories for studying the cords in built up motor tyres. The canvas or the cords in an ordinary tyre are shown in a radiograph, and certain defects of construction can be thus revealed (Fig. 42).

Accurate measurements of small hidden objects may be made from a radiograph by making allowance for the geometrical enlargement of the shadow. The fit of screw threads may also be examined. In Fig. 43 natural sized radiographs of some small screw threads are shown, together with an enlarged reproduction. These pictures give an idea of the detail that may be obtained by the use of a fine focus X-ray tube at a good distance from the specimen. Photographic plates of the class known as process plates are best for this type of work because of their very fine grain.

Only the very briefest mention can be made of some of the other purposes for which X-rays have been employed during recent years. They have been used in a commercial laboratory as a means of observing the height of a mercury column inside a steel tube. Abrasive wheels have been examined for incipient cracks which might cause them to burst when rotating at high speeds. Fireclay pots for use in the manufacture of glass have been inspected for the presence of harmful metallic impurities. X-rays are said to have been employed by chocolate manufacturers to ensure the absence of metallic particles, by Customs authorities to investigate the contents of sealed packages, and for the detection of pearls in oysters. Real pearls may be distinguished by their fluorescence under the rays, and

imitation precious stones, which are frequently made of glass of high density, may be detected by their opacity when compared with the genuine article. Many people are now familiar with the small X-ray outfits installed in certain bootmakers' shops, by means of which a customer may see the fit of his shoe and its effects on the bones of his foot pictured on a fluorescent screen.

Still another interesting application of radiography is the examination of old oil paintings. The pigments used hundreds of years ago were generally mineral in nature, whilst in more recent times vegetable or coal tar colours have been largely employed. The result is that, in general, the older pigments are more opaque to X-rays than the more modern. This fact has enabled many interesting discoveries to be made of alterations to old pictures, the old pigments being revealed through the paint which has covered them, in some cases, for several centuries.

Although hardly to be classified as industrial applications, mention must be made of the beautiful results obtained in the radiography of plant life—leaves, flower buds, fruit, etc.—and also of shells, fossils and meteorites. Then, too, a great deal has been heard recently of the X-ray examination of mummies in Egypt. Thus does this most modern form of light help to illuminate the secrets of the dead past as well as the mysteries of the living present.

Here we must end our brief and incomplete catalogue of the applications of Rontgen's X-rays. That many more will be added to the list in the near future seems certain. The radiologist does not know the problems of industry. He can only offer his rays as a new tool to the industrialist, and leave it to him to suggest the particular problems in his own sphere which they may help to solve. We can only hope that these pages may help to a better understanding of what the new tool is and what it is capable of and so assist in some small measure the progress of X-rays in industry.

CHAPTER XVIII

AT RANDOM

THE history of the development of X-rays covers a very short period—just a little over thirty years. It affords a very remarkable illustration of the achievements of intensive research. It was a semi-accidental discovery, and yet it has gone far in altering scientific conceptions. Modern medicine and surgery, if they were deprived of the assistance of X-rays, would lose efficiency to an extent that can hardly be imagined, notwithstanding the fact that their use was deprecated by a very eminent medical authority in the early days.

In the realm of industry X-rays have yet to be established, and such is the conservativism of modern business that an enormous amount of energy must be expended (and so wasted) in explaining obvious applications to sceptical individuals and organizations. Endeavours to introduce new scientific methods into practical business has ever proved an arduous task. It took many years to demonstrate the utility of the microscope in metallurgy. The most powerful factor operating against innovation is the old and indisputable fact that " my father did perfectly well without it." This idea, even when not expressed in words, is a convenient mental armchair in which to indulge the inherent laziness that characterises the solid British business man. It is somewhere on record that when gun sights were first suggested, the contemplation of such an unnecessary and revolutionary change produced a

sort of mental syncope in thc person of the exalted and gallant officer to whom the matter was referred for consideration.

Modern scientific discovery, while it is pregnant with new dogmas and avenues of hope for all sorts and conditions of men, is bewildering in the prolixity of its paradoxes. It is the necessity for exact correlation of observed phenomena which entails such kaleidoscopic changes in the scientific picture gallery of to-day. Perhaps the most certain thing about modern scientific theory is its transience.

It is quite impossible to forecast what we shall ultimately think about energy and its propagation. As we have endeavoured to show in this book, philosophy has succeeded philosophy, and even now our exact knowledge concerning things that really matter is negligible. We have identified the electron, and now we must be prepared for the question which the inhabitants of our nurseries will surely ask : What is it made of ? We have seen that it was the discovery of radiation of extremely short wave length that enabled us to analyse the atom and to form such a graphic picture of the way in which it is built up. Instead of regarding the atom as an ultimate unit, we now talk of the electron as the smallest expression of mass that we know. It remains for us to find out the nature of the electron. Furthermore, we have a whole universe to explore in the nucleus of the atom. We have already some idea of the complexity of the structure involved from the experiments of Sir Ernest Rutherford. We know that under certain conditions the atomic nucleus will break up spontaneously, and that when it does so certain elements are ejected from it. We also know that experimental ingenuity has enabled Sir Ernest Rutherford to disintegrate atom nuclei at will, but even so, very little is known of the atomic nuclear system. It may be that within this infinitesimal though ponderous mass there

are other planetary systems which are so small that even X-rays and the gamma rays of radium are powerless to produce the effects which would enable us to appreciate them.

Any further investigation into the nature of matter would seem to be bound up with a knowledge of the phenomenon of energy, which is probably the most fundamental thing in experience. It is unquestionable that if a complete knowledge of the relationship of energy and matter were known, then the whole riddle of the universe would be solved. It is this consideration which confers such a romantic, we might almost say an ecclesiastical, character on the science of physics !

Scholastic philosophy and the exact sciences may appear at first sight to be alien schools of thought, but a study of modern physics renders it a matter of extreme difficulty to determine the borderline where exact measurements must stop and philosophical speculation begin. Perhaps " progress" is a wrong expression to apply to scientific development. Re-adjustment of view-point is brought about as fresh expressions of nature are observed, and very often these adjustments appear to be even retrograde in character. For example, in the study of atomic phenomena it appears that we may be forced to regard light as sometimes corpuscular, and to throw overboard the classical theory which has been so firmly entrenched for years. It may be that new phenomena, as yet only hinted at, will oblige us once more to change our view concerning the nature of light. It is the first essential in a man of science that he should possess the mental flexibility and discipline that will enable him to receive and examine every new manifestation, not in any spirit of hostile criticism, but rather with an earnest desire to make use of every particle of work that is done, however vague its application may appear.

It is sometimes amusing when we look back, secure in

our later knowledge, to recall erroneous condemnation of certain steps in progress, but at the same time the spirit of ignorant dogmatism which often prompted such criticism, has done, and is doing, infinite harm. It is a spirit fatal to the ultimate welfare of the race. Progress is now very apt to be defined exclusively in terms of mass production and balance sheets, and consequently the more indirect steps, though vital in importance, are very often stifled in their infancy. The nourishment they should receive is all expended on the tares which may be represented by the now popular quick sales and quick returns.

At the present time it is of the greatest importance that the general public should be induced to take the most active interest in all scientific development. Science must no longer be regarded as something apart—something of a mystic nature concerned with crucibles and absent-minded professors in velvet caps. The intensive development of science will only yield practical advantages when the present deplorable public apathy is replaced by intelligent enquiry and the intimate interest of the whole community.

Not the least important result of the development of X-rays has been that they have formed a common link between other branches of science that hitherto had drifted into something approaching independent existences. By the use of X-rays we have been brought to a more defined realization of the essentially physical nature of our bodies. The discovery that these new rays had very definite action on physiological tissue led to enquiry as to the nature of the changes they produced. It was at once apparent that parallel phenomena could be produced in the laboratory of the physicist. The fact that in all probability our bodies were but special differentiations and arrangements of electrical charges became much more tangible and appreciable than it had been hitherto. Thus, X-rays have proved a most valuable stimulus in the

development of that particular line of scientific activity which we call biological physics.

Although the value of sunlight treatment was advocated many years ago on empirical grounds, it was not until the nature of radiation in general was more thoroughly investigated and understood that full advantage was taken of the marvellous curative properties of that particular part of the spectrum known as the ultra violet—the next door neighbour of X-rays. In the domain of chemistry, too, X-rays have had a most important influence. They have been instrumental in emphasising the fundamental electrical nature of the elements and of the manner in which they combine with each other.

In the province of practical electrical science the new physics have been most potent. Hertzian waves have been harnessed to give us wireless fireside concerts and communication with distant parts of the world. We must remember that wireless waves are exactly the same in nature as X-rays, and only differ in wave length. The electron, too, that ubiquitous parent of X-rays, has been of the greatest practical service in enabling us to construct that modern marvel, the wireless valve.

In mechanical engineering the value of X-rays is just on the threshold of its career of usefulness. Many of the problems which confront the metallurgist have resisted and exhausted all known methods of attack. Problems concerning the exact nature of the structural modifications produced in metals by heat and other treatment are to a very considerable extent still unsolved.

In a previous chapter we have seen how it will be possible, with every prospect of success, to apply X-rays to such problems. Instead of the comparatively gross view which alone has been possible hitherto, we shall be able to substitute an analytical survey of the arrangement of the tiny constituent atoms which are so potent in determining important physical properties in metals.

In addition to this work which is rather specialised and must be confined to the laboratory for a long time before it can be developed into a factory method, there is the more practical application of radiography in the service of the mechanical engineer.

The application of X-rays in searching for flaws and defects in engineering materials has already been discussed. The method is as yet immature, but at the same time the fact that the interior of solid structures may be examined without cutting them up has obviously a very high potential value. One of the greatest difficulties encountered in modern engineering is the weakness of materials. Any method that offers a possibility of confirming the soundness of castings and forgings should be encouraged and used on every possible occasion. It has been shown that this particular technique has developed enormously during the last few years, and there is definite reason for believing that further progress is possible. The lines of research are well known. They should be prosecuted with all possible energy. The cost of engineering work on castings is very considerable, and as the casting or forging is larger the cost of subsequent machining work increases by a very large factor. The full value of X-rays in this work will not be realised until it is possible to examine castings and forgings of six or even eight inches in thickness. Because of the known inherent weakness of materials, the factor of safety in engineering construction is probably unduly high, resulting in increase of size and weight, which in some structures particularly is so very undesirable. It is a matter of satisfaction that the British Government has adopted X-ray examination of materials for many purposes, including factory engineering products and in aeroplane construction. In America the practice is also followed with the result that remarkable improvements in engineering work have been reported.

We have remarked that the lines of future X-ray re-

search are known. This fact indeed represents not the least important result of the research that has already been carried out. Arduous investigation of the new phenomena that are ever occurring in X-ray experiments, particularly when dealing with ultra high voltages, has served to indicate certain lines of development which can hardly be expected to yield practical results. On the other hand, it has brought to light properties which may be easily adapted to urgent requirements. It may justly be said that this statement is true of all scientific research, but it is particularly applicable to X-rays, where all the work is entirely new and contributary work is very scarce.

From the point of view of medical treatment by X-rays and also the radiography of heavy metal castings and forgings, we must have X-ray tubes that will work at extremely high voltages, certainly up to half a million volts. The construction of such tubes is a matter of great difficulty, and physical problems are involved which demand a very high degree of skill and experience in their solution. We are faced with a condition of affairs where a glass envelope contains myriads of atomic universes thrown into violent movement and internal eruption by the electrical conditions which are applied.

In order that we may stabilize the conditions inside this envelope we must acquire some knowledge of the way in which these myriads of atoms react as electrical conditions are varied. Materials such as glass and refractory metals, of which X-ray tubes are usually made, have properties which are very thoroughly understood in all ordinary circumstances; but these properties are by no means the same when forces are applied to the materials which produce abnormally violent agitation in their constituent atoms. Glass, which normally is vacuum tight, may conceivably become as porous as sponge, and complicated chemical changes may be evolved which produce a set of conditions entirely unanticipated.

In the first place, then, radiological research must concern itself with the production of a stable ultra high voltage X-ray tube. Dr. W. D. Coolidge, of Schenectady, New York, conferred the greatest boon on radiology by the introduction of the Coolidge hot kathode tube in 1913. We also owe a great debt to Dr. Coolidge, in that he has presented one of his original tubes to the Science Museum at South Kensington. It is a piece of apparatus of very great historic value, a possession of which British radiologists should be very proud. The hot kathode is the key to the problem of the high voltage tube we require, and research therefore is primarily concerned with development along these lines.

Of all the energy that is supplied to an X-ray tube in the form of electrical power, less than one per cent. emerges in the form of X-rays. The rest of it is, as we say, degraded and is dissipated as heat. Some time or other radiologists will have to give attention to this matter, as the inefficiency of an X-ray tube is alarming. The problem involved is by no means a simple one, as heat would appear to be an essential concomitant in the production of X-rays. It may be, however, that this wasted energy may some day be re-transformed and serve as a valuable factor where now it is such a drawback. A slightly parallel case occurs to us at once. In the early days of ordinary telephony the phenomenon known as induction was a bugbear, and every effort was made to eliminate it. It is curious to observe that this same execrated induction has now made wireless telephony possible.

The question of the provision of electrical generators for X-rays is by no means as acute as the need for better tubes. Transformers have already been constructed to deliver current at voltages far higher than anything we can possibly use for X-rays. The present X-ray problem from this aspect is concerned with the *nature* of the high

tension current supplied to the X-ray tube. It is necessary to study the various forms of high tension current that are possible and to examine the quality of X-rays they engender. Some work along these lines has already been done, but very great improvement in X-ray efficiency may be expected, as research in this direction proceeds.

The fact that the radiologist can demonstrate cracks and holes in castings is not enough for the engineer. He wants to be told what the flaws mean. Considerable time is being spent, therefore, in endeavours to determine the depth and dimensions of these metallic flaws, in order that they may be expressed in terms of mechanical strength. The problem is not difficult, but it must be developed into something very simple and definite before X-ray examination can be a factory routine operable without specialised assistance.

The fact that X-rays can be used to examine metallic welds without damaging the specimen seems to promise a very wide sphere of useful activity. It is certain that if a reliable method of determining the soundness of a weld could be used, then welding would be adopted to a much larger extent than it is at present. This is particularly true of shipbuilding, where riveting is now so widely employed. The possibility of using X-rays to examine ship welds *in situ* has been considered, and the problem seems to be capable of solution. It will be necessary to design and construct X-ray plant of great power capable of being slung over the side of a ship. The design of such equipment is a matter of great difficulty, but nevertheless this particular application of X-rays has such importance that it warrants the devotion of care and time to a consideration of the problem.

Important problems are continually being submitted for X-ray investigation. Some of these are within the sphere of usefulness of X-rays, some are beyond it. Specialised X-ray research must concentrate on these new

problems, any one of which may so benefit by the use of X-rays that the money expended on research would be repaid with substantial interest.

A good deal has been written in the past few years against the waste involved in overlapping in scientific research. No doubt the frenzied search for avenues of economy (preferably as remote from the searcher as possible) is responsible for a good deal of this criticism. It is a short-sighted policy. A certain amount of overlapping in research is not only desirable but it is absolutely necessary. So much depends upon accuracy that corroboration of scientific results is always imperative. Moreover, professional rivalry and criticism are the best and most efficacious stimuli in any activity, and as the well-being of humanity at large is so bound up with scientific progress, it should be the first care of the nation to ensure that, what ever else goes short, scientific research should be amply endowed. It is devoutly to be hoped that war is a thing of the past. If this hope is so sanguine as to result in wholesale reduction of armaments, then scientific research, at least for purposes of national defence, is doubly essential, at any rate until such time as science herself has made it possible to effect radical alterations in that fundamental entity which we call human nature.

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